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RADIOPHYSICS. 1965-1966
RADIOPHYSICAL INVESTIGATIONS OF VENUS

by A. D. Kuzmin

All-Union Institute of Scientific and Technical Information,
Academy of Sciences USSR, Moscow, 1967

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RADIOPHYSICAL INVESTIGATIONS OF VENUS

A. D. Kuz'min

The publication "Radiophysical Investigations of Venus" provides a survey of radio astronomical and radar measurements of Venus, which are basic sources of contemporary information concerning this planet. The results of information concerning physical conditions on Venus, obtained on the basis of these investigations, are summarized. This issue is intended for specialists working in the areas of radio astronomy, planetary astronomy, and space investigations, and also for astronomers, astrophysicists, geophysicists and representatives of allied specialties interested in the physics of the planet.

Introduction

With the development of cosmic flights, planetary investigations have become one of the basic directions of contemporary astronomy. Special interest has arisen in the study of physical conditions on Venus, the closest planet in the solar system to the earth. /5*

Venus is the brightest luminary in the sky after the sun and the moon. Discovered before our era, Venus for centuries has attracted the attention of astronomers. Due to its relative proximity to the earth (at its lowest point the distance to it is approximately 40 million km), Venus, it would appear, must be well studied. However, much less information has been acquired concerning this planet than for example Mars, which is at a point of great opposition, i.e., once in 17 years it approaches only to within 60 million km of the earth.

During the long history of investigations of Venus, even such fundamental characteristics of the planet as temperature and state of aggregation of surface matter of the planet were not determined. Even the diameter of the planetary body, or its period and the direction of its rotation around its axis, were unknown.

* Numbers in the margin indicate pagination in the foreign text.

The dense cloud layer of the planet, rendering the planet practically inaccessible to optical observations, is the basic reason for such a scarcity of information concerning Venus.

New methods for Venus research were discovered only during the last decades, when radio astronomy, and later radar astronomy, came to the aid of optical astronomy.

In connection with the fact that the earth cloud layer has a "transparent window" in the range of radio waves we may anticipate the presence of an analogous "transparent window" in the range of radio waves in the cloud cover of Venus as well. In conducting measurements of the characteristic radio emissions and radar reflections from Venus through this "transparent window" we may obtain information concerning the surface of the planet inaccessible to optical investigations. However, information in available literature concerning studies of Venus utilizing these methods is quite incomplete and often contradictory.

An attempt is made in this monograph to sum up radio astronomical and radar observations of Venus for a period of 10 years, including information obtained concerning the physical conditions on this planet based upon these observations. /6

The material in this book is arranged in the following order. The status of research on physical conditions on Venus, based upon data obtained through optical observations, is explained in the first chapter.

The theoretical premises of radiophysical investigations of Venus are stated in the second chapter. The theory of radio emanation of a planet with a radiation absorbent atmosphere is examined. The relationship between parameters measured in radio astronomic and radar observations, and the physical characteristics of the planet has been determined.

A survey of the results of radio astronomic and radar measurments of Venus at the mid-1966 stage is given in the third chapter.

The fourth chapter is devoted to the consideration of available experimental data and to defining the physical conditions on Venus.

In the conclusion the direction of further investigations of Venus is projected.

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CHAPTER 1

A SHORT SURVEY OF DATA CONCERNING VENUS OBTAINED FROM OPTICAL OBSERVATIONS

1. Motion of the Planet /7

In distance from the sun, Venus is the second planet of the solar system. Its average distance from the sun comprises 0.723 astronomical units, i.e., approximately 1.4 times less that that of the earth. The orbit of Venus is almost circular (eccentricity 0.0068) and is inclined toward the plane of the earth's orbit by 3° 24 min.

The period of revolution of Venus around the sun (sidereal period) includes 224.7 earth days.

In its movement relative to the sun and the earth, Venus presents to the earth observer phases similar to the phases of the moon. In the inferior conjunction when Venus is located between the earth and the sun, the dark side of the planet not illuminated by the sun is turned toward the earth. This phase is analogous to the new moon. In the superior conjunction Venus is located almost exactly behind the sun and turns its illuminated side toward the earth. This phase is analogous to the full moon. In intermediate positions Venus passes through all intermediate phases of a partially illuminated disk similar to moon phases. The interval of time between two identical phases, which is called the synodical period, is equal on the average to 584 earth days. A list of the conjunctions of Venus from 1950 until the year 2000 borrowed by us from [74] is given in Table 1 of the appendix.

The problem of the parameters of rotation of Venus has been the subject of numerous investigations; since the year 1666, i.e., for 300 years, more than 100 articles have been published.

First determinations of the parameters of rotation of the planet were based upon attempts to reveal permanent details on the planetary disk and to track their visual movement. Such an attempt was made by D. Cassini [131]. In observations of the movements of "spots" on the visible disk of Venus /8
carried out in the year 1666, he concluded that the period of rotation is equal to 23 hours and 21 minutes. However, subsequent observers of Venus were unable to note any kind of detail on Venus, and could not even confirm the presence of the "spots."

Sixty years later, Bianchini [112] again observed details on the planetary disk, and even drew up a map of Venus representing "oceans" and "continents." In accordance with the displacement of these details which were in his opinion constant, he obtained a period of rotation equal to 24 days and 8 hours. The ecliptic coordinates of the pole of Venus were determined by him to be $\lambda_p = 320°$, $\beta_p = 75°$, thus the inclination of the planet's equator to the plane of the orbit would be 15°.

In the course of the following 150 years a majority of observers obtained values approaching 23 hours for the period of rotation of Venus. In the year 1887, a thoroughly excellent result was obtained by Schiaparelli [291]. He determined that the rotational period of Venus equaled the period of its revolution around the sun (224.7 days), and therefore that Venus always turned the one side toward the sun. Dollfus [148] came to the same conclusion based upon an analysis of many years of visual and photographic observation of Venus.

Such a large difference in the results of the determination of the rotational period of Venus is explained by the fact that the surface of the planet is covered with a dense cloud layer. Actual details within the cloud layer are so unclear and nonstationary that even the fact of their existence is doubtful.

In this connection the observations of N. P. Barabashev [8], carried out from August 30 to September 20, 1964 of a large black patch on Venus are interesting. Significant changes in both the coloring of the patch and its visibility are noted. Thus on August 31 and September 3 the patch was highly visible, but by September 19 had completely disappeared.

Observations in the infrared portion of the spectrum, in which some forms of haze and mist are transparent, were also without result. However, photographs obtained in 1926 by Ross utilizing ultraviolet rays [227] unexpectedly revealed dark bands lying approximately perpendicular to the terminator. The changing positions of these bands from day to day testified to their atmospheric origin. Ross estimated the rotational period as close to one month. These bands, discovered by Ross, were confirmed in 1950 and 1954 by Kuiper [207], who, proceeding from the hypothesis that the bands were stretched along the planetographic parallels of Venus, defined the coordinates of the north pole of the planet as

$$\alpha_p = 53° = 3^h32^m; \quad \delta_p = 81°,$$

which corresponds to a 32-degree inclination of the equator to the orbital plane. The presence of bands in Kuiper's opinion indicates comparatively rapid rotation around the axis. /9

Analogous observations were carried out in 1954 and 1955 by Richardson at the Mt. Wilson observatory [275]. He obtained north pole coordinates.

$$\alpha_p = 311° = 20^h44^m; \quad \delta_p = 64°,$$

which corresponds to a 14-degree inclination of the equator to the orbit.

Still another attempt was made to define the position of Venus's pole by Zotkin and Chigorin [32], who carried out visual observations of white patches and bulges on the limb. It was noted that the appearance of these details corresponded to the established geocentric longitudes of Venus. Assuming that these bulges were cloud formations connected with the "cold pole" of Venus, the author defined the coordinates of the pole as

$$\alpha_p = 8^\circ = 0^h32^m; \quad \delta_p = 62^\circ,$$

which corresponds to an inclination of the equator to the orbit of 39°.

Detailed research of the bands observed in the ultraviolet portion of the spectrum were carried out by Boyer and Camichel.

Boyer [120] having carried out photography of Venus in 1957, 1959 and 1960, noted a four-day recurrence period of detail. In explaining this result he advanced the hypothesis, in agreement with which the rotation period of Venus is close to 96 hours and the rotational axis is approximately perpendicular to the plane of the ecliptic.

Camichel [127], having carried out a comparison of his own photographs with those obtained at other observatories, and separated in time by several hours, in many cases detected a displacement of details corresponding to retrograde rotation.

For more detailed investigation, Boyer and Camichel [121] combined their photographs and selected the best of them. An analysis of the material obtained led them to the conclusion of the presence on the apparent surface of the planet of a consistently existing dark formation having the form of the letter Y laid on its side: ≺ . Separate parts of this formation appearing on the illuminated part of the disk had, due to rotation, created a discrepancy in the visible picture of the disposition of dark and light zones.

In utilizing material derived from observation, which was collected at Pic du Midi from 1948 to 1960 and at Brazzaville from 1957 to 1960, and having added to this the observations of Danzhon of November 10, 1962, the authors could take advantage of data encompassing a 14-year period of time. The point /10
of convergence of three bands forming the Y-shaped detail was taken by them as a point of reference. Measurements of the shift of this point on all selected photographs gave an average synodic rotation period equaling 96 hours and 33 minutes. Under the assumption of perpendicularity of the rotation axis to the orbit of the planet and retrograde rotation, they determined that the siderial period of rotation of Venus equals 97 hr, 38 min. An attempt to process these same measurements under an assumption of normal rotation did not succeed.

According to observations in 1963 and 1964, Boyer and Camichel [122, 123] also obtained a periodicity of four days with variations within limits of from 3.5 to 4.5 days. They explained both these variations and the latitudinal shift of the patches by citing local movements of cloud masses which are also observed in the form of patches and belts.

Guinot [178] obtained analogous results concerning the rotation period of Venus (4.1±0.7 days) and concerning its retrograde rotation.

Notwithstanding the constancy of this Y-shaped marking, the establishment of the rotation period of Venus in accordance with its displacement cannot be considered reliable. In fact, the possibility of the presence of not one but several similar Y-shaped markings successively appearing on a disk cannot be excluded. In this case the true rotation period would be four days multiplied by an integer number. Besides this, the interpretation of the observed periodicity as rotation is not the only possibility. Thus it may be assumed, for example, that periodically recurring meteorological phenomena take place in the atmosphere of Venus generating the appearance of dark bands.

Spectroscopic methods of investigation of the rotation of Venus have also not yielded definite results. First observations carried out from 1900 to 1911 by A. A. Belopol'ckiy [11, 12] revealed a shift in the lines of the edge relative to the center of the visible disk of the planet, corresponding to a rotation period of Venus of 1.44 days. However, analogous spectroscopic measurements made by Slipher [297, 298] indicated a much slower rotation with the period exceeding 15 days.

Later spectroscopic observations carried out in 1956 by Richardson [276] also revealed that Doppler shifts resulting from rotation concealed mistakes in measurement. On this basis Richardson considers that one of the following possibilities may be true: 1) retrograde rotation with a period from 8 to 46 days; the probability of this is 1/2; 2) the period is greater than 14 days /11
if the rotation is direct, and more than 5 days if the rotation is retrograde; the probability of this is 16/17; 3) the period is greater than 7 days if the rotation is direct and more than 3.5 days if retrograde; the probability of this is 134/135.

2. Dimensions, Mass and Density

Venus is related to the planets of the earth group and has approximately the same dimensions, mass and average density as the earth. To calculate the ephemeris, the diameter of Venus was taken as 12,200 km, i.e., 0.956 of the diameter of the earth; at a distance of one astronomical unit, this corresponds to an angular diameter of 16.82". In agreement with Martynov's [68] appraisal and a following critical review by Vaucouler [324] compiled on the basis of a series of observations and carried out over the last 100 years, the diameter of the visible disk of Venus comprises 12,240±15 km. Measurements of the shape of Venus carried out during the time of its passage across the solar disk did not reveal any kind of deviation of the disk from a circle. In practice therefore the visible figure of Venus may be considered to be a globe. The altitude of the cloud layer over the surface of the planet, and therefore the diameter and shape of the planet itself, are unknown.

The mass of Venus is 408,500±160 times less than the mass of the sun [138], which corresponds to 0.815 of the earth. The density of Venus is 4.86 g/cm^3. For the earth the corresponding quantity is equal to 5.52 g/cm^3. Acceleration of gravity on the surface of Venus $g_♀$ = 835 cm • sec^{-2}. The second cosmic speed near the surface of Venus is equal to 10.2 km/sec.

3. The Atmosphere and the Cloud Layer

The atmosphere of Venus was discovered in 1761 by M. V. Lomonosov [66] after having observed the passage of the planet across the solar disk. However, up to the present time the composition of the atmosphere, temperature and the pressure are practically unknown. Such a situation results mainly from the fact that due to the nontransparence of the atmosphere of Venus in the optical range only the upper layers of the gaseous-aerosol clouds of the planet are accessible to our immediate investigation. At the present time the lower cloud layers remain the subject of diverse hypotheses.

An evaluation of the pressure in that part of the atmosphere above the clouds of Venus was carried out by Dolfus [27], Moroz [71, 72] and Vaucouler and Menzel [323]. Dolfus investigated the difference in polarity in the red and green parts of the spectrum. Interpreting this as a result of molecular scattering, he determined that the equivalent altitude of the at- /12
mosphere of Venus at the level of the cloud layer was equal to 800 meters. Under a force of gravity somewhat less than that of earth, this corresponds to a pressure at the top of the cloud layer of 90 mb*. V. I. Moroz in widening the band of absorption CO_2 λ 1.575 and 1.606 μ defined the pressure at the level of the cloud layer as equal to 300 mb.

Vaucouler and Menzel [323] in accordance with observations of the screening of Regulus by Venus, evaluated the pressure at a level of 70 km above the cloud layer as equal to 2.6 x 10^{-3} mb. In accordance with these observations the altitude of the similar atmosphere in the layer above the clouds of Venus equals H = 6.8 km according to the calculation of the authors, and H = 6 km according to the calculation of Martynov and Pospergelis [67].

According to a calculation of Sagan [282] based upon measurements of the bands of absorption CO_2 λ 0.8 μ [302] and 1.6 μ [191], and the screening of Regulus by Venus [323], the pressure at the level of the cloud layer for the illuminated side of Venus was determined to be equal to 600 mb.

* We are reminded that 1 atm = 1013 mb.

An attempt to estimate the pressure in that part of the atmosphere under the clouds was undertaken by Spinrad [302]. He processed old spectrograms of the spectrum band 7820 Å, obtained by Adams and Dunham [102]. They calculated the pressure at the level of the reflecting layer from 1.1 to 4.6 atm according to the spread of the spectral lines. In connection with the fact that high pressures correspond as a rule with high temperatures, they interpreted the result as an indication of change in the altitude of the reflecting layer. At the lowest measured level the pressure approached 5 atm.

The chemical composition of the atmosphere of Venus has been the subject of numerous spectroscopic investigations. Nevertheless, thus far carbon dioxide is the single satisfactorily explained component of the atmosphere of the planet.

Estimates of the content of CO_2 in the atmosphere of Venus have been extremely diverse. Until recently the most accepted estimates have been those of Adams, Dunham [102] and Kuiper [41]. According to these estimates there exists above the cloud layer 10^5 atm-centimeters* of CO_2, which appears to be the basic component of the atmosphere of Venus. Completely different results were obtained recently by Spinrad [302]. Having processed the old spectrograms of Adams and Dunham he determined the CO_2 content to be equal to 2×10^5 atm-centimeters. However, in accordance with measurements of the width of the lines of absorption, he came to the conclusion that the indicated quantity of CO_2 is maintained above the level at which the pressure comprises 7 atm. In this case there is above the cloud layer (under a pressure at the level of this layer of 90 mb) only 4×10^3 atm-centimeters of CO_2, and the relative content of carbon dioxide in the atmosphere of Venus consists in all of 4% (according to the mass). /13

According to an estimate of Kaplan [193] the relative content of CO_2 in the atmosphere of Venus comprises 15%.

Under earth conditions, atmospheric carbon dioxide reacts with silicates, which are components of soil. This process, decreasing the content of CO_2 in the atmosphere, demands the presence of water in the liquid state as a catalytic agent. The liberation of CO_2 into the atmosphere proceeds simultaneously with this. The speed of these processes is determined by the

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* 1 Atm-centimeter is the thickness in cm of the layer of specified gas which would be obtained if the gas were isolated and compressed to a pressure of 1 atmosphere under the influence of a standard temperature.

equilibrium of Urey. The abundance of CO_2 in the atmosphere of Venus in comparison with that of earth indicates apparently a disturbance in the equilibrium of Urey. A possible reason for this may be the lack of water on Venus.

A series of attempts to detect water in the atmosphere of Venus have been undertaken.

In 1921 Jōhn and Nicholson [188] investigated at Mt. Wilson the line of water vapor near λ 5,900 Å. This line was not detected. They calculated the upper limit of the water vapor content above the reflecting layer of Venus as equal to 1 mm of precipitated water, i.e. about 14% of the content of water vapor in the atmosphere of the earth over Mt. Wilson in winter.

Adams and Dunham [102] carried out analogous investigations of the line near 8,200 Å and estimated the upper limit of the water vapor content on Venus as equal to 5% of the earth's level.

In 1960, with the aid of an apparatus raised on a stratospheric balloon in order to decrease terrestrial lines, Strong and others undertook measurements of the band of absorption of water vapor near λ 1.13 μ. It was found that the water vapor content above the reflecting clouds in the atmosphere of Venus comprises $(1.9 \pm 1.6) \cdot 10^{-3}$ cm, i. e. (19 ± 16) μ of precipitated water. However, in connection with the fact that the water vapor content measured by Strong and others is commensurate with that found in the atmosphere of earth [243], the cited data were subject to doubt.

In 1962 Spinrad [301] reprocessed some old Mt. Wilson spectrograms near λ 8,180 Å. He detected no line of absorption of water vapor. He calculated the upper limit of water vapor content in the atmosphere of Venus as $7 \cdot 10^{-3}$ $g \cdot cm^{-2}$ (70 μ). From a comparison with former work defining the pressure in accordance with the spreading of lines of absorption of CO_2 [302] he considered that the experiment referred to the level at which the pressure consisted of 8 atm and therefore the relative content of water vapor in the atmosphere of Venus would be less than $9 \cdot 10^{-7}$ (according to the mass). This calculation was reduced to $<10^{-5}$ because of a series of indefinite quantities.

The next attempt to detect water vapor was undertaken by Dollfus [150] in 1963 by measurements of the band of H_2O near λ 1.4 μ. In comparing the spectrum of Venus and the moon under conditions of equal zenithal distances he detected that in all cases the intensity of the band of H_2O in the spectrum of Venus was higher than in the spectrum of the moon. He determined that the average water content of the Venus disk was equal to $2.8 \cdot 10^{-2}$ $g \cdot cm^{-2}$. These measurements were carried out with a phase angle of 91° which corresponds to 4 as the average optical path of the reflected ray. From this the water vapor content in a vertical column was calculated as equal to $0.7 \cdot 10^{-2}$ $g \cdot cm^{-2}$, i.e. 70 μ. Providing that the calibration of the apparatus was carried out under pressure of 1 atm and that the pressure /14

Spectroscopic investigations of the nonilluminated part of the Venus disk conducted by Kozyrev [39] revealed the presence of characteristic radiation of the lower layers of the atmosphere of Venus's dark side. The spectrum of this radiation is, in all probability, identifiable with bands of formaldehyde (HCHO).

Suess [314], on the basis of a study of the history of Venus and its development from an initial cloud similar in composition to the composition of the sun, considers it probable that neon is the basic component of the atmosphere of Venus.

In summarizing the above it may be stated that the atmosphere of Venus differs from that of the earth by greater density, significantly greater content of carbon dioxide and significantly lower content of water vapor and oxygen. There are no established data concerning other gases. It is possible that nitrogen is the basic component of the atmosphere of Venus.

The albedo of Venus is a function of wave length. It is maximum at a wave near 1 μ and diminishes rapidly both in the ultraviolet and in the infrared portions of the spectrum [72].

The high reflection capability of Venus to visible light is usually connected with its clouds. Data concerning the nature of the clouds is quite contradictory. Indices of diffusion of Venus obtained by Barabashev, [7], Sobolev [86], Fesenkov [93] and others through photometric observatic .s display a greatly extended form. This points to the diffusion of light by rather large scale particles, i.e., to the presence in the atmosphere of a large quantity of aerosol and to the insignificance of molecular diffusion of light. Polarimetric observations of Venus carried out by Lyot [223] demonstrated that the polarity of the reflected solar light depends upon the phase of Venus. According to his observations the polarization is equal to 0 at the time of the superior conjunction and maximum at dichotomy. We will consider that the observed polarization of Venus is similar to the polarization of transparent spherical elements such as water drops 2.5 μ in diameter. However, Van de Kholst [6] points out that the polarization data may be just as well satisfied by quartz dust with an average particle diameter of 5 - 10 μ. /17

Spectroscopic measurements by Strong and others [118] in the region of 1.7 to 3.4 μ revealed a spectral curve corresponding excellently with a laboratory curve of the image of ice crystals. However, Deirmendjian [144] did not consider this comparison to be sufficient proof of the presence of ice crystals in the clouds of Venus because of the difficulty in reproducing in the laboratory ice crystals with dimensions corresponding to those in the clouds. In addition, Deirmendjian remarked that the Venus spectrum obtained by Strong and others [118], agrees with a spectrum of dense earth cirrus clouds obtained by Blau and Espinola [114]. Small differences may be explained apparently by taking multiple diffusion into account.

Kaplan [195] also does not consider Strong's data to be a suitable argument in favor of the existence on Venus of ice clouds due to the fact that a gap in the spectrum obtained by Strong, and attributed by him to ice crystals, may have resulted from absorption by carbon dioxide.

According to estimates by Moroz [70], produced in accordance with a maximum position on the albedo spectral curve, the mean diameter of reflecting particles $r \cong 1\ \mu$. The last estimates by Dolfus [151] were carried out in 1964 at the Pic du Midi observatory. These estimates based on measurements of the index of diffusion, reveal the diameter of the reflecting particles to be 1.5 to 2 μ.

4. Temperature

The problem of the temperature of the planet is extremely important for a Venus physicist. The first radiometric measurements of the temperature of Venus in accordance with the intensity of planetary radiation were carried out by Pettit and Nicholson [259] in the spectral interval 8--14 μ. The luminance temperature in the center of the disk was determined by him to equal on the average 240° K for the nonilluminated side and 235° K for the illuminated side of Venus. /18

It is necessary to emphasize immediately that in connection with the nontransparency of the atmosphere of Venus in the infrared range, both the data cited above and the following data concerning the temperature of the planet refer to its cloud layer.

Subsequent measurements by Sinton and Strong [295] in the spectral interval 8--13 μ, carried out using a more advanced method, revealed an analogous result: the average temperature at the center of the disk was determined to equal 234° K, and the difference in temperature between the illuminated and the nonilluminated sides of the planet did not exceed several degrees. Later measurements by Sinton [296] on waves 8.8 and 11.9 μ, produced at various phases, also did not reveal any kind of phase shift. The average temperature was determined to equal 234.3 ± 5.4° K. On one of the days of observation (September 29, 1960), a rise in temperature to 257° K was noted which, in the opinion of the author, may have reflected a temporary change in conditions in the atmosphere of Venus. The high resolution (1".4) resulting from the use of the 200 inch telescope of the observatory on Mt. Palomar permitted Sinton and Strong to obtain the distribution of brightness on the planetary disk in the directions east-west and north-south. Darkening of the limb in comparison with the center was detected. Equatorial distribution of brightness is well approximated by the correlation

$\cos^{1/2}\theta$, where θ is the planetocentric angular distance from the center of the disk. In the directions perpendicular to the plane of the ecliptic, the edges of the limb are colder (by 8--10° K) than in the directions corresponding with this plane. A cold region near the north cap of the planet was detected through observations in 1953. This region is possibily connected with a bright cloud previously observed by photography in the ultraviolet spectrum.

In 1959 Sinton repeated the indicated measurements with a 42" telescope with lower resolution [75] and also obtained darkening of the limb.

In 1962 Murray, Wildey, and Westphal [244] carried out radiometric measurements of Venus with a 200" telescope approximately one month after the inferior conjunction. A resolution of 1".5, which corresponded to 1/30 of the Venus disk permitted them to formulate a map of the distribution of brightness temperature on the planetary disk. Isophotes of brightness temperature are drawn out in a parallel direction to the orbital plane of the planet and confirm the conclusion of Sinton and Strong [295] concerning a larger darkening near the poles. Difference in temperature between the dark and the light parts of the planet were not detected. A local hot area was revealed on the southern part of the disk. Its temperature and dimensions changed /19
from day to day, while at the same time the temperature of the remaining part of the disk remained constant.

In 1964 these investigations were continued from December, 1963 to August, 1964. The isophotes obtained display a displacement of the area of maximum brightness temperature from the center of the disk to the side opposite the sun. This circumstance, and also a decrease in the absolute value of the brightness temperature near the inferior conjunction in comparison with measurements in December, 1963 at small phase angles, leads the authors to the conclusion that the point opposite the sun is several degrees warmer than the point near the sun. The presence of a hot area near the south pole in the region of the terminator was confirmed.

Chase, Kaplan, and Naugebauer carried out analogous investigations of the infrared radiation of Venus utilizing methods of high resolving power from the cosmic station "Mariner-2" [135]. Measurements took place in two spectral intervals 10.2--10.5 and 8.1--8.7 μ. Five measurements on the dark side, five on the light side, and eight along the terminator were carried out. Brightness temperatures in the indicated spectral intervals, the first of which corresponds to a band of absorption, and the second to a window of transparence of CO_2, proved to be identical. Darkening of the limb in comparison with the center was observed at approximately 20° K. Brightness temperature in the center of the disk is 240° K. Brightness temperatures of the dark and light sides of the planet are identical. A detail was registered in the southern part of the terminator which was colder than the surrounding area.

Radiometric measurements on the shorter wave 3.75 μ were carried out by Sinton [296] and revealed a brightness temperature of 236° K, close to that obtained in the interval 8--13 μ.

Chamberlain and Kuiper [132] undertook to determine the temperature of Venus through the measurement of rotary-vibrational bands 8,689 and 7,820 Å. Assuming an optically isotropic-scattering atmosphere, they obtained a temperature of 285 ± 9° K. Kuiper detected also an attentuation in the CO_2 band λ 8, 689 Å relative to the CO_2 band 8,498 Å at an increased phase angle. In reprocessing old Mt. Wilson spectrograms in the region of the CO_2 band λ 7,820 Å, Spinrad [302] obtained analogous attentuation of lines at an increased phase angle. However, the most important result obtained by Spinrad proved to be the high temperatures of rotary junctions, which changed for various days of observation from 214 ± 6 to 445 ± 31° K.* In connection with /20 the fact that higher temperatures correspond as a rule with higher pressures, variations in temperature are interpreted by him as changes in the altitude of the radiating layer, rather than changes in the depth of penetration of this radiation into the atmosphere of Venus.

As indicated earlier, all of the data cited above concerning temperature obtained through measurements in the infrared band, refer to the cloud layer of the planet. An estimate of the temperature of the stratosphere of Venus was made by Rasool [273], through data obtained by observation of the covering of Regulus [323] by Venus. His estimates set the temperature of the mesopause near 200° K.

Due to the nontransparence of the atmosphere of the planet in the infared range, it is not possible through optical observation to measure the temperature of the surface of the planet itself.

5. The Magnetic Field

The first attempt to evaluate the magnetic field of Venus was undertaken by Houtgast [183, 184]. As a basis for research the assumption was made that the magneto-sphere of Venus serves as a screen for solar corpscular streams and therefore, near the inferior conjunction of Venus, when the planet is located between the sun and the earth, one may expect a reduction in geomagnetic activity of the sun on the earth. An analysis of the results of measurements of geomagnetic activity, carried out since 1890 from approximately 27 inferior conjunctions of Venus and in periods of weak solar activity, displayed an actual reduction in solar geomagnetic activity when the proximity of Venus to the sun (by latitude) was closer than 4.5°. Numerical evaluations of the magnetic fields have been made under additional assumptions concerning the nature of solar corpscular streams. Thus if this is a stream of protons thrown off by the sun with a speed of 500 km/sec, the revealed screening effect must correspond to a magnetic field of Venus 5 times greater than that of earth. If the corpscular cloud is electrically neutral, the magnetic field of Venus must be evaluated at 5,000 times greater than that of earth.

* In contrast to Chamberlain and Kuiper [132], Spinrad determined the temperature under the assumption of a nondiffusing Venus atmosphere which, in comparison with [132], raises somewhat the temperature values which he obtained.

The results of the evaluations cited above are in sharp contradiction with data obtained through measurements of the magnetic field in the area around Venus carried out in 1962 by Mariner 2 [299]. These measurements have shown that at a distance of 41,000 km from Venus, the magnetic field of Venus does not differ from the interplanetary (< 10 γ)*. An appraisal of the field /21 near the surface of the planet depends upon the form of the magneto-sphere of Venus. Such an appraisal for various forms, carried out by Spreiter and Jones [307], Lees [215], Smith and others [299], and Spreiter [308], lead to the magnetic dipole moment of Venus from 1/2 to 1/30 of that of the earth with the most probable value near 1/20.

In summarizing the above, it may be stated that Venus is a type of planet with a nontransparent atmosphere, and therefore only the upper layers of its gaseous-aerosol cloud are accessible to optical investigation. The composition of and the conditions existing in the lower level and on the surface are the subjects of diverse hypotheses. Of the numerous suppositions concerning this problem, expressed at various times and by various authors, we note the following three:

1. Conditions exist analogous to those that took place on the earth in the carboniferous period, i.e. an all-encompassing warm and damp climate with an abundance of moisture, and a constantly dull sky. The organic world is approximately at that state of development which took place on the earth at the end of the paleozoic era. Such a point of view was widespread at the end of the last and at the beginning of the present century when it was assumed that the cloud cover of the atmosphere of Venus consisted of condensed water.

2. Conditions exist reflecting the presence of an absolutely waterless desert. This point of view arose in connection with results of contemporary spectroscopic investigations. This is usually connected with the organogenic theory of the derivation of oxygen of the earth atmosphere: the complete lack of water was an obstacle to the development of vegetation, and the lack of the latter was the reason why the atmosphere of Venus preserved its initial carbon-nitrogen composition.

3. There exists an unbroken ocean completely covering the whole surface of the planet. This hypothesis was advanced in connection with the fact that interaction between carbon dioxide and rocks of the surface would have led to various chemical reactions, to the absorption of carbon dioxide by the surface and to the formation of rocks of carbonaceous composition. In the opinion of the authors of this hypothesis, the thickness of the water isolating the surface from the atmosphere promotes the preservation of the composition of the latter from change.

The sharp contradiction of the points of view cited may serve as an illustration of the scarcity of data obtained through optical observations concerning Venus.

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* 1 $\gamma = 10^{-5}$ oersted.

CHAPTER II

THEORETICAL PREMISES OF RADIOPHYSICAL INVESTIGATIONS OF VENUS

For convenience, in paragraph II.1 below there is presented some information concerning radio astronomy, mainly touching upon terminology, a definition of the relationship between basic parameters which characterize the observed radio emissions of the planet, and the mechanism of thermal radio emission. /22

Some information from radar astronomy is also presented in paragraph II.3.

Readers familiar with radio and radar astronomy may pass over these sections.

1. Some information concerning radio astronomy

Radio astronomy is that branch of astronomy which is involved in the study of diverse cosmic objects through the analysis of their characteristic radiation in the radio wave range.

Radio emanations from these objects create on the earth an electromagnetic field, the density of flux energy which is given by

$$S = \iint I(\nu, \Omega)\, d\nu\, d\Omega. \qquad \text{(II.I)}$$

Here I is the energy flux radiating from a solid angle element $d\Omega$ of the object investigated in the frequency interval $d\nu$, which is passing in a unit of time through a unit area in the direction normal to this area. Thus the defined quantity I is the brightness. The I dependence on frequency defines the frequency spectrum, and on direction in space defines the angular spectrum of radiation.

Investigations of the intensity of radiation, its frequency in angular spectra and polarization, its changes in time and in connection with various types of optical phenomena are the basic sources of information in radio astronomy concerning the nature of cosmic objects.

For a quantitative characteristic of the intensity of radiation of cosmic objects, brightness, flux density and brightness temperature are used.

We defined the meaning of brightness I above.

Flux density S, which is defined in accordance with (II.1), characterizes the total energy which is being emitted from a source of radiation under investigation in one band of frequencies, passing through a unit of space and one unit of time and in a direction normal to this space.

Integration (in II.1) takes place within the limits of the solid angle Ω of the source being investigated, because outside these limits the integral is equal to zero.

For sources small in comparison with the width of the directional pattern of the radio telescopes (which is usually the case for planets), the measured quantity is the flux density S. In a practical system, units of S are expressed in $wt \cdot m^{-2} h^{-1}$.

Brightness and flux density of cosmic sources depend upon frequency. However, within the limits of the passband of the measuring device it may be considered to be constant. This enables us to characterize the intensity of the radiation of brightness temperature T_b. This is defined as the temperature of an absolutely black body, having at a given frequency and in a given direction the same brightness of heat radiation as the observed source.

In the radio band the connection between brightness and brightness temperature is defined by the relationship

$$I = \frac{2kT_b}{\lambda^2}, \qquad \text{(II.2)}$$

where k is Boltzmann's constant,

λ is the wave length of the received radiation.

Brightness temperature, and in general brightness, depends upon the coordinates of the radiating area $T_b = T_b(\Omega)$ and also characterizes the distribution of the intensity of the radiation along the source being investigated.

Flux density is connected with brightness temperature by the following apparent relationship

$$S = \frac{2k}{\lambda^2} \int_{\Omega} T_b(\Omega)\, d\Omega. \qquad \text{(II.3)}$$

For a source having at all points identical brightness temperature T_b,

$$S = \frac{2kT_b}{\lambda^2} \Omega_S, \qquad \text{(II.4)}$$

where Ω_s is the solid angle of the source of radiation.

For sources with a nonisotropic brightness temperature, we utilize the concept of brightness temperature, averaged in accordance with its solid angle /24

$$\overline{T}_b = \frac{1}{\Omega_s} \int_{\Omega_s} T_b(\Omega)\, d\Omega. \qquad \text{(II.5)}$$

In the case of Venus we are speaking of the brightness temperature averaged according to the planetary disk $\overline{T}_{b♀}$. Brightness temperature is expressed in absolute degrees Kelvin.

Flux density is connected with the brightness temperature, averaged in accordance with the visible disk by the relationship

$$S = \frac{2k\overline{T}_{b♀}}{\lambda^2} \Omega_♀, \qquad \text{(II.6)}$$

where $\Omega_♀$ is the solid angle of the visible disk of Venus.

Convenience in utilizing the concept of brightness temperature proceeds from the fact that in the case of thermal radiation, T_b is related by a very simple relationship with the kinetic temperature of the source T, and with a sufficiently thick radiating layer it equals simply T.

Intensity characterizes the total flux, which is being radiated by the source in two right-angled polarizations. If the radiation undergoing investigation is not polarized, the energy is distributed equally between the indicated polarizations.

The linearly polarized component of the received radiation is characterized by the degree of polarization p and the positional angle Ψ. The degree of polarization is determined by the relationship

$$p = \frac{I_\Psi - I_{\Psi+90°}}{I_\Psi + I_{\Psi+90°}}, \qquad \text{(II.7)}$$

where I_ψ and $I_{\psi + 90°}$ are the brightnesses of radiation with the orientation of the electrical vector in a direction corresponding with the plane of polarization ψ and in a right angle direction. The degree of polarization is usually expressed in a percentage.

The spectrum of radiation may be on the whole a complex function of frequency. However, within restricted limits it may be described as a function $I_\nu = a\nu^{-n}$, where n is a constant which is called the spectral index of radiation. The value n is determined by the mechanism of radiation.

The power of the radiation of a cosmic source is a directly measurable quantity by feeding the antenna output to the input of the radiometer.

The intensity of the signal at the antenna output is conveniently characterized as the equivalent temperature of the source received by the antenna. For brevity it is usually called simply the antenna temperature of the source T_A. /25

For a non-polarized source the antenna temperature is related to the flux density of its radiation S by the relationship

$$T_A = \frac{SA}{2kg}. \qquad \text{(II.8)}$$

Here

$$g = \frac{\int_{\Omega_S} T_b(\Omega)\, d\Omega}{\int_{\Omega_S} T_b(\Omega)\, F(\Omega)\, d\Omega} \qquad \text{(II.9)}$$

is a coefficient taking into account the commensurability of the angular dimensions of the source and the directional pattern of the antenna, A and $F(\Omega)$ are the effective area of the antenna of the radiotelescope and a function describing its directional pattern, respectively.

In the calculation of g during planetary observations it is possible to obtain a diverse distribution of radioluminescence. In this connection, and in agreement with [58],

$$g = \frac{1}{1 - 0{,}326 \left(\frac{\varphi_p}{\varphi_A}\right)^2}, \qquad \text{(II.10)}$$

where ϕ_p and ϕ_A are the angular diameter of the planet and width of the directional pattern of the antenna at the level of -3 db.

The antenna temperature T_A of the source of radiation under investigation is measured with the aid of a calibrating device within the radiometer, which also includes special noise generators [58].

The planetary brightness temperature T_b, averaged in accordance with the visible disk, is calculated in accordance to the measurement of its antenna temperature T_A from the relationship

$$\overline{T}_b = \frac{\lambda^2}{A\Omega_p} T_A g \qquad \text{(II.11)}$$

However, the determination of the value of the effective area of the antenna of the radiotelescope A, especially for large radiotelescopes with which measurements of planetary radiation are carried out, presents in practice a very difficult problem. In addition, the value A usually depends upon the position of the radiotelescope and does not remain constant in the process of observation. For example, the effective area of the radiotelescope antenna at the University of Michigan at the wavelength 3.75 cm decreases by 18% at an antenna inclination of h = 50° to h = 10° [145]. Inaccuracy in the determination of A introduces into the desired quantity T_b a systematic error, the value of which usually reaches approximately 10%. It is necessary to keep this circumstance in mind when comparing the data of various observations, for example, for investigations of the frequency spectrum. A more exact comparison of various measurement data may be effected if the radiation intensity measurement of a planet is carried out in comparison with the radiation intensity of some other cosmic source, taken as a standard, or if such a source is used for measurement of A, and the source parameters, obtained by the authors, are indicated.

The angular spectrum of radiation $I(\Omega)$ (or $T_b(\Omega)$) characterizes the distribution of radioluminescence along the source undergoing investigation. To realize this it is necessary to have an antenna system having a directional pattern width much less than the angular dimensions of the object undergoing investigation. The angular diameter of Venus, even near the inferior conjunction, consists in all of only about one minutes, and demands the use of an antenna with an angular resolution consisting of a part of an angular minute. In the utilization of contemporary earth radiotelescopes such a pattern has thus far not been obtained, even on the shortest millimeter waves. However, the indicated difficulty may be avoided through the application of a radiointerferometer antenna system.

The simplest two-element interferometer consists of two antennas spaced at distance D, connected with transmission lines and working with one receiver (Fig. II.1).

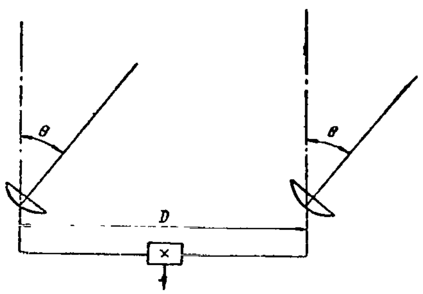

Figure II.1. Schematic of Dual-Antenna Radiointerferometer.

A horizontal wave arrives from a direction perpendicular to the line (called the base of the interferometer) connecting the phase centers of the spaced antennas. Due to equal transmission-line length, signals from both antennas add in phase and the intensity of the signal received is maximum. If the /27 direction of the arrival of the signal differs from the normal direction, the sum of the signals from the two antennas takes place out of phase, resulting in a lower intensity of the resultant signal. With the motion of the source being investigated across the sphere of the sky, the direction of the arrival of the signal in relation to the base of the interferometer constantly changes, and therefore the resultant signal changes in accordance with the rule

$$1 + F(\beta)\cos\left[\left(\frac{2\pi}{\lambda}\right) D \sin\theta\right],$$

where θ is the angle between the direction to the source and normal to the base of the interfermometer. In the general case for the interferometer with any orientation of the base, the angle θ is defined from the relationship

$$\sin\theta = \sin\delta_b \sin\delta + \cos\delta_b \cos\delta \cos(t - t_b),$$

where δ_b and t_b are the inclination and the hour angle of the pole of the base of the interferometer, δ and t are the inclination and hour angle of the source undergoing investigation.

The relative (referred to the constant component) amplitude of the interferometer record of the source F (β) is called a visibility function. The visibility function is the normal spatial Fourier-transformation of the radioluminescence T_b (x,y) of the investigated source in the direction x of the effective base of the interferometer. For a source having the shape of a disk

$$F(\beta) = \frac{\int\limits_0^1 \cos 2\pi\beta x \int\limits_0^{\sqrt{1-x^2}} T_b(x, y)\, dy\, dx}{\int\limits_0^1 \int\limits_0^{\sqrt{1-x^2}} T_b(x, y)\, dy\, dx}, \tag{II.12}$$

$$\beta = \frac{D_e}{\lambda} r, \tag{II.13}$$

where D_e is the effective length of the base of the interferometer, r is the angular radius of the disk, λ is the wavelength at which the measurements are being made.

In solving the problem in reverse on the basis of the measured Fourier-distribution F (β) and with the aid of the inverse Fourier-transformation, it is in principle possible to find the actual distribution of the radioluminesence of the investigated object T_b (x,y). However in this operation one must keep in mind the following considerations:

a) The dual-antenna radiointerferometer is a linear instrument investigating only unidimensional distributions of radioluminosity in the direction of the effective base of the interferometer. Thus for the investi- /28
gation of two-dimensional distributions of radioluminescence it is necessary to carry out measurements at different orientations of the effective base of the interferometer relative to the source undergoing investigation.

The directional angle of the effective base of the interferometer χ* is determined by the relationship

$$\sin\chi = -\frac{\cos\delta_b \sin(t - t_b)}{\cos\theta} \qquad (II.14)$$

In this manner it is possible to change the orientation of the effective base of the interferometer relative to the source both by changing the orientation of the interferometer itself (by changing δ_b and t_b), and by observation of the source at various hour angles t.

b) Since at a fixed spatial frequency β various distributions of radioluminescence may correspond to the same Fourier-components, to locate the true distribution of radioluminescence it is necessary to measure the visibility function F (β) in as large a range as possible of the spatial frequencies β, i.e., at various effective bases of the interferometer D_e.

The latter are obtained through conducting measurements on the base of changing length. The value D_e is defined by the relationship

$$D_e = D\cos\theta. \qquad (II.15)$$

In this manner, and within the restricted limits, changing the length of the effective base of the interferometer is also possible through changing the hour angle.

In connection with the difficulty in locating the inverse Fourier-transformations, usually direct Fourier-transformations are calculated for various models of distribution of radioluminescence and from these models the Fourier-transformations closest to the experimentally measured visibility function of the object under investigation are chosen.

In conclusion we will stop briefly on the mechanism of thermal radiation, which plays an important role in the interpretation of radiation from Venus.

In general, radiation of electro-magnetic waves is connected with changes in the energy of motion of charged particles. Depending upon conditions under which these changes take place, we distinguish between thermal and non-thermal radiofrequency radiation. Thermal radiation arises in a medium, the particles of which are in chaotic thermal motion. This radiation is described by the classical laws of heat radiation, which are /29
descriptive of the radiation of light and heat from heated bodies.

On the basis of the theory of thermal radiation, there exists a connection between the capability of matter to radiate and absorb electromagnetic waves, which is specified by Kirchoff's Law. In the case of a body located in

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* The angle χ is read counter-clockwise from the source hour circle.

thermodynamic equilibrium, the intensity of radiation is determined by the well known (see for example [99]) relationship

$$I = \kappa B(T), \tag{II.16}$$

where κ is the coefficient of absorption and temperature of the radiating medium and B(T) is a Planckian function of radiation which, in the radio frequency range, becomes a Rayleigh-Jeans function:

$$B(T) = \frac{2kT}{\lambda^2}. \tag{II.17}$$

For an absolutely black body, $\kappa = 1$ and its intensity of radiation at a given temperature is maximum. The brightness temperature of radiation of an absolutely black body is equal to its temperature T. Since real cosmic sources are not absolutely black, the brightness temperature of their thermal radiation in general will be lower than their temperature.

In the case of thermal radiation every elementary act of radiation is random, but the full intensity of the radiation is equal to the sum of the intensities of the separate radiators. Therefore even if a radiating medium is not in thermodynamic balance (for example, it may consist of electrons speeded up by an electric field), and the radiation of each electron is not connected with the radiation of other electrons, such radiation also has a thermal character. However if the number of radiators is very great, the intensity of the emitted radiation is limited by the absorption capability of the radiating particles. A transfer equation of radiation gives a quantitative analysis of the indicated process.

$$\left.\begin{array}{c} dI = -\varkappa I ds + \varkappa B(T)\, ds \\ \text{or} \\ \dfrac{dI}{d\tau} = -I + B(T) \end{array}\right\}, \tag{II.18}$$

where

$$d\tau = \kappa ds.$$

The value

$$\tau_s = \int_0^s \varkappa ds, \tag{II.19}$$

representing the optical thickness or the optical depth of the medium characterizes attentuation of the wave, spreading out from the layer situated at distance s from the point of observation. We obtain the brightness of /30 radiation of a medium with optical thickness τ, observed at point O, through integrating (II.18) along the line of sight.

$$I = \int_0^\tau B(\tau) e^{-\tau} d\tau + I_0 e^{-\tau}, \quad \text{(II.20)}$$

where I_0 is the brightness of radiation, falling upon the layer from outside (from the direction opposite the observer). If $I_0 = 0$ or $\tau >> 1$, from equations (II.2) and (II.17) we find that the brightness temperature of thermal radiation of the medium is equal to

$$T_b = \int_0^\tau T(\tau) e^{-\tau} d\tau. \quad \text{(II.21)}$$

In particular, if $T(\tau) = T = \text{const}$, i.e., the medium is isothermic, then

$$T_b = T(1 - e^{-\tau}). \quad \text{(II.22)}$$

An optically thick medium, for which $\tau >> 1$, has maximum brightness temperature $T_b = T$, independent of τ; such a medium may be considered to be absolutely black. On the contrary, if $\tau << 1$, then $T_b \cong \tau T$. Such a medium is considered to be optically thin; its brightness temperature is proportional to its optical thickness. If the temperature of the medium changes along the line, the basic part of the radiation of an optically thick medium proceeds from the layer, for which $\tau \cong 1$.

Thus the intensity of thermal or radiowave radiation depends upon the optical thickness of the radiating medium. Depending upon physical processes within the medium, the amount of absorption and its dependence on wavelength are distinguishable.

For planets having an atmosphere and possibly an ionosphere one may expect the presence of thermal radiation of the surface and of the layers mentioned. Therefore we will dwell briefly on the mechanism of radiation and absorption in the indicated mediums.

The ionosphere, on the whole, is a neutral gas-like medium, a part of the atoms of which are ionized. Electrons, torn from atoms in connection with their chaotic thermal motion under the influence of a Coulomb field of positive ions, change direction and velocity which leads to irradiation of electromagnetic waves. On the other hand, electromagnetic waves distributed within the plasma spend part of their energy on oscillation of electrons. Due to collision of the later with ions, the energy of the electromagnetic waves is transformed partially into thermal motion.

The coefficient of absorption in an ionized gas may be presented in general form by the relationship /31

$$\varkappa = \frac{1}{2c\mu\varepsilon_0} \frac{4\pi e^2}{m} \frac{N\nu}{\omega^2 + \nu^2}, \tag{II.23}$$

where N is the electron concentration, ν is the frequency of collisions, ω is the circular frequency of the received radiation. In the ionosphere usually $\nu^2 << \omega^2$, but the frequency of collisions is determined by collisions with ions

$$\nu_{ei} = 6.1 \cdot 10^3 \left(\frac{300}{T_e}\right)^{3/2} N_i, \tag{II.24}$$

where T_e is the kinetic temperature of the electrons. Substituting (II.23) and (II.24) in (II.19), and considering that in the ionosphere $N = N_i$, we find that the optical thickness of such an ionized gas

$$\tau \sim \lambda^2 \int_0^s \frac{N^2}{T_e^{3/2}} ds, \tag{II.25}$$

i.e., grows in proportion to the square of the wavelength. This dependence $\tau(\lambda)$ leads to a definite form of curved dependence of brightness temperature on wavelength. Comparing (II.22) and (II.25) it is easily noted that on sufficiently short waves, while $\tau << 1$, the brightness temperature must increase in proportion to the square of the wavelength. With even further increase in λ, the medium becomes optically thick ($\tau << 1$) and brightness temperature becomes greatest, but independent of wavelength. A typical graph of changes in T_b as a function of λ is presented in Figure II.2.

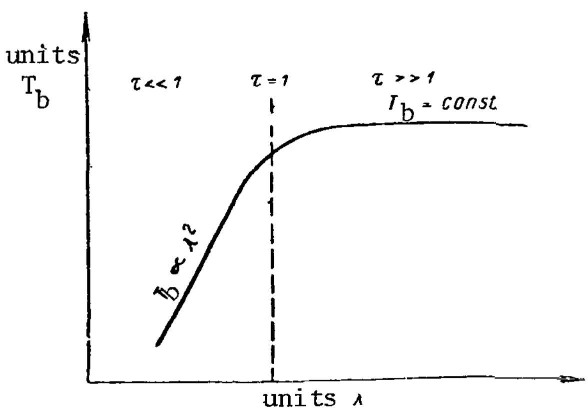

Figure II.2. The Distribution of Brightness Temperature of Thermal Radiowave Radiation.

The mechanism of absorption /32
and radiation referred to above does not take place when all of the atoms of a gas are neutral and lack free electrons. However, another mechanism is possible in which the gas may absorb radiation diffusing within it, and in accordance with Kirchhoff's Law the gas itself may radiate. This mechanism consists of the excitation of the bound charges in non-symmetrical molecules by a passing electromagnetic wave. These molecules have a magnetic or electric dipole moment with subsequent transfer of the energy of oscillations of these charges into heat, under the influence of collisions with other

atoms or molecules.

The absorption of such gases has a resonant character. Of the most widespread molecules within the range of the wavelength utilized by radio astronomy, water vapor (H_2O) and oxygen (O_2) have intensive lines of absorption corresponding to wavelength 1.35 and 0.5 cm. There are also many lines of absorption of water vapor in the millimeter wavelength range.

For waves longer than 5 mm the coefficient of absorption in water vapor may be stated by the expression [89]

$$\varkappa_{H_2O} = \frac{SN\nu^2 e}{T}\left[\frac{\Delta\nu_1}{(\nu-\nu_{01})^2+\Delta\nu_1^2}+\frac{\Delta\nu_1}{(\nu+\nu_{01})^2+\Delta\nu_1^2}\right]+\frac{S'Ne\nu^2\Delta\nu_2}{c^2T}. \qquad (II.26)$$

The first element here is determined by the resonant absorption on $\lambda =$ $= 1.35$ cm, and the second by the contribution of all resonances on the highest frequencies. The constants S and S' are determined by the parameters of the molecule, N is determined by the whole number of molecules in 1 cm^3 of gas, e is determined by the number of molecules H_2O, and T is determined by the temperature of the gas.

Under normal conditions the lines of absorption are relatively sharp and the value of absorption decreases rapidly with distance from resonance. However, with an increase in gas density the lines of absorption broaden. In heavily compressed mediums the lines may fuse.

Absorption in gases, which under normal conditions are transparent for radiowave radiation, may take place at raised pressures. The reason for this is the deformation of the molecules during collisions which causes for a short time asymmetry of the molecule, and a dipole moment which causes nonresonant absorption of ultrahigh frequencies. The coefficient of such absorption, termed induced absorption, is proportional to the square of the pressure p and to the square of the frequency ν and is determined by the relationship

$$\varkappa = \varkappa_0 \frac{p^2\nu^2}{T^m}. \qquad (II.27)$$

The exponent m amounts to approximately 3.5 to 4.5. /33

The theory of thermal radiowave radiation of the surface of the planet will be examined in § II.2.

2. The Theory of Radiowave Radiation of a Planet with a Radiation-Absorbent Atmosphere

For an interpretation of the results of radio astronomic investigations, it is necessary to establish a connection between measured values and the physical parameters of both the surface and the atmosphere of Venus, which influence the character of its radiation. Among these parameters are the temperature and radiating capability of the surface, and also the temperature and absorption in the atmosphere [59].

In connection with the fact that the overwhelming majority of contemporary radiotelescopes still do not have the resolving power sufficient to isolate parts smaller than the Venus disk, the brightness temperature averaged in accordance with the visible disk of the planet $\overline{T}_{b♀}$ is the usual measured quantity. In this connection it is necessary to find the relationship between the averaged brightness temperature and the planetary parameters mentioned.

For a planet devoid of atmosphere a similar problem was set and solved by V.S. Troitskiy [90,92]. Heiles and Drake [182] also examined the case of Venus, devoid of an atmosphere.

However Venus, as is well known, is surrounded by an atmosphere which may prove to be absorbent and therefore also radiant within the radio frequency band. Besides this, there may still be some kind of radiation absorbent layer above the surface of the planet. Therefore it is worth-while to examine both the radiation of the surface of the planet itself and the influence on it of the absorbent mediums mentioned.

Barrett [106] examined a similar problem only for the particular case of molecular absorption in H_2O and CO_2 in connection with the exponential distribution of absorbent matter.

We will solve in general form the problem of determining radiation of an elementary area on the disk of a planet with atmosphere.

The brightness temperature of radiation of an element of the surface is [90]

$$T_b = T_{e0} (1 - R). \tag{II.28}$$

Here R is the coefficient of reflection of the examined element in the direction of the observer, and

$$T_{e0} = \int_0^\infty T(y)\,\varkappa(y) \sec\theta' e^{-y\varkappa \sec\theta'} dy,$$

where T(y) and κ(y) are the true temperature and coefficient of absorption of planetary matter at depth y, θ' is the angle between the direction of the radiation, proceeding from inside, and the normal of the output surface. The atmosphere in a general case weakens the radiation of the surface and moreover radiates itself. A layer of atmosphere of thickness ds in the line of sight, and located over an element of the surface being investigated, has absorption /34

$\kappa(s,\lambda)$ ds. The total optical thickness of the atmosphere is

$$\tau(\lambda)=\int_0^{\infty}\varkappa(\lambda,s)\,ds.$$

Therefore the brightness temperature of the combined radiation of a surface element and of the atmosphere in the line of sight over the element will equal:

$$T_b[\tau(\lambda)]=T_{e0}(1-R)e^{-\tau(\lambda)}+\int_0^{\infty}T_a(s)\varkappa(s,\lambda)\,e^{-\int_s^{\infty}\varkappa(s,\lambda)}ds. \qquad (II.29)$$

The parameters R, $\tau(\lambda)$, $T_a(s)$ and $\kappa(\lambda,s)$, which enter into this formula in a general case depend upon the position of an element of the surface relative to the observer. Experimentally observed phase variations of brightness temperature points out also that at least some of the observed parameters depend also on illumination of the sun and therefore on the position of the radiating element relative to the sun. The temperature of the absorbent atmosphere $T_a(s)$ and the absorption in it are also functions of the altitude above the surface of the planet.

As a first approach, let us assume that the phase variations of the brightness temperature, averaged in accordance with the visible disk of Venus, is determined only by differences in the effective temperatures of the surface $T_{e0\,o}$ and $T_{e0\,\bullet}$ and the parameters of the atmosphere τ_o, $\tau_\bullet$, T_{ao} (s), $T_{a\bullet}$, κ_o (s) and $\kappa_\bullet$ (s) of the illuminated and non-illuminated parts of the planet in the changing relationship between these two parts on the visible disk. Within limits, we will consider constant all of the indicated parameters of each of these parts.

Then, at the upper and lower conjunctions, when the illuminated side or the non-illuminated side of the planet is respectively fully turned toward the earth, we may consider T_{e0}, $\tau(s)$, $T_a(s)$ and $\kappa(s)$ independent of the position of the element on the surface of the planet relative to the sun.

For an examination of the dependence of T_b on the position of the radiating element relative to the observer, it is convenient to utilize the polar system of coordinates a, γ, where a is the distance of the element from the center of the disk, expressed in fractions of the radius of a disk, and γ is the angle at the center of the disk between the direction of the origin of the calculation and the direction to the radiating element. As the origin /35
of the calculation we shall take a direction corresponding with the polarization of the receiving system. Dependence of the coefficient of reflection on the coordinates of the radiating element is described by the relationship

$$[1-R(a,\gamma)]=(1-R_V)\cos^2\gamma+(1-R_H)\sin^2\gamma, \qquad (II.30)$$

where R_v and R_h are the coefficients of reflection for vertical and horizontal polarization. For a smooth (in comparison with wavelength) surface the coefficients of reflection are determined by the well known formula of Frénel:

$$\left.\begin{aligned} R_v &= \left(\frac{\varepsilon\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}\right)^2, \\ R_h &= \left(\frac{\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}\right)^2, \end{aligned}\right\} \tag{II.31}$$

where ε is the dielectric permittivity of the material of the surface. Taking into consideration that $a = \sin\theta$ and by carrying out elementary transformations, we obtain the following relationships for the radiation capability in vertical and horizontal polarizations:

$$\begin{aligned} E_v &= 1 - R_v = \frac{4\varepsilon\sqrt{(1-a^2)(\varepsilon - a^2)}}{(\varepsilon\sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2} \\ E_h &= 1 - R_h = \frac{4\sqrt{(1-a^2)(\varepsilon - a^2)}}{(\sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2}. \end{aligned} \tag{II.32}$$

The thickness of an elementary absorbent layer in the direction of the line of sight is

$$ds = \frac{dh}{\cos\theta} = \frac{dh}{\sqrt{1-a^2}}, \tag{II.33}$$

from which

$$\tau(s) = \frac{\tau(h)}{\sqrt{1-a^2}}. \tag{II.34}$$

Through the calculation above, the brightness temperature of an element of the surface with coordinates a, γ may be expressed in the form

$$\begin{aligned} T_b(a,\gamma,\lambda) = T_{e0}\Bigg[&\frac{4\varepsilon\sqrt{(1-a^2)(\varepsilon - a^2)}}{(\varepsilon\sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2}\cos^2\gamma + \\ &+ \frac{4\sqrt{(1-a^2)(\varepsilon - a^2)}}{(\sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2}\sin^2\gamma\Bigg] e^{-\frac{\tau(\lambda)}{\sqrt{1-a^2}}} + \\ &+ \frac{1}{\sqrt{1-a^2}}\int_0^\infty T_a(h)\varkappa(h,\lambda)\, e^{-\frac{1}{\sqrt{1-a^2}}\int_h^\infty \varkappa(h,\lambda)dh}\, dh. \end{aligned} \tag{II.35}$$

It was pointed out earlier that, upon reception by an antenna with a broad directional pattern in comparison to the angular dimensions of the planet, the brightness temperature averaged in accordance with the visual disk of the planet is the measured quantity /36

$$\overline{T}_{bp} = \frac{1}{\Omega_p} \int_{\Omega_p} T_b (a, \gamma)\, d\Omega, \tag{II.36}$$

where Ω_p is the solid angle of the planet.

In the chosen system of coordinates the element of the solid angle is

$$d\Omega = \frac{\Omega}{\pi} p a d a d\gamma. \tag{II.37}$$

Having substituted (II.35) and (II.37) in (II.36), and carrying out a series of transformations, we obtain

$$\overline{T}_b(\lambda) = \overline{T}_1 (\lambda) + \overline{T}_2 (\lambda). \tag{II.38}$$

Here $\overline{T}_1(\lambda)$ and $\overline{T}_2(\lambda)$ are the components of brightness temperature, averaged in accordance with the visual disk, resulting from radiation of the surface and of the atmosphere of the planet, respectively.

The quantity $\overline{T}_1(\lambda)$ depends upon the temperature and the electrical characteristics of the surface and on the total absorption within the atmosphere

$$\overline{T}_1 (\lambda) = T_{e0} I_1 [\tau (\lambda), \varepsilon], \tag{II.39}$$

where

$$I_1 [\tau (\lambda), \varepsilon] = 4 \int_0^1 a \left[\frac{\varepsilon \sqrt{(1-a^2)(\varepsilon - a^2)}}{(\varepsilon \sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2} + \frac{\sqrt{(1-a^2)(\varepsilon - a^2)}}{(\sqrt{1-a^2} + \sqrt{\varepsilon - a^2})^2} \right] e^{-\frac{\tau(\lambda)}{\sqrt{1-a^2}}} da. \tag{II.40}$$

The quantity $I_1[\tau(\lambda), \varepsilon]$ is in fact the radiation capability of the planet averaged in accordance with the visual disk. Numerical values for the different parameters τ and ε, computed on the calculating machine, are presented in Table 2 of the Appendix. Figure II.3 is a graph of the function of $I_1[0, \varepsilon]$ for the case $\tau = 0$, i.e., for waves for which atmospheric absorption does not take place. On this diagram is shown the dependence on ε of the radiating capability of the disk normal to the line of sight.

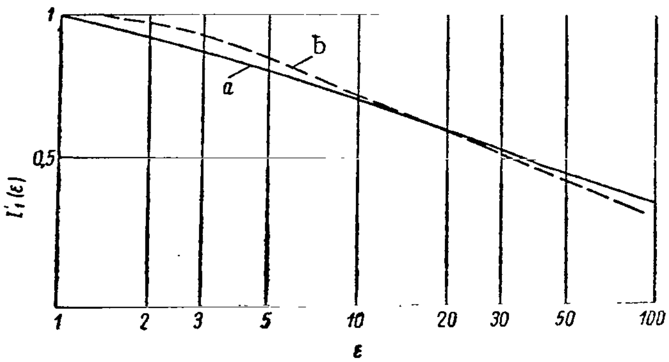

Figure II.3. Dependence of the Radiation Capability of a Planet with a Transparent Atmosphere on the Dielectric Constant ε of the Material of the Surface.
a) averaged in accordance with the visual disk; b) for a normal slope.

The relationship (II.39) determining the radiation of the surface of a planet was obtained for a case when the radiating layer was isothermic, when in actual fact on the surface of the planet there may be areas with a different temperature. In introducing /37
the concept of true temperature averaged in accordance with the visual disk

$$\bar{T} = \frac{1}{\Omega}\int_{\Omega} T\, d\Omega, \qquad \text{(II.41)}$$

we may, for the small quantities ε which interest us, with sufficient accuracy generalize (II.39) in the case of any distribution of temperature

$$\bar{T}_1(\lambda) = \bar{T} l_1[\tau(\lambda), \varepsilon]. \qquad \text{(II.42)}$$

The component of brightness temperature $\bar{T}_2(\lambda)$, resulting from radiation of the atmosphere, depends upon temperature and absorption in the atmosphere and the distribution of these parameters according to altitude:

$$\bar{T}_2(\lambda) = 2\int_0^1 \frac{a}{\sqrt{1-a^2}} \int_0^\infty T_a(h)\,\varkappa(\lambda, h) \times \exp\left(-\frac{1}{\sqrt{1-a^2}}\int_h^\infty \varkappa(\lambda, h)\, dh\right) dh\, da. \qquad \text{(II.43)}$$

For further calculations we will make several assumptions concerning these parameters.

The distribution of temperature in the atmosphere of Venus is taken as a piecewise linear temperature gradient β_1 from the surface to the upper /38
limits of the cloud layer and β_2 above the cloud layer, i.e.,

$$T_a(h) = \begin{cases} T_{ps} + \beta_1 h & \text{for } 0 \leqslant h \leqslant h_{cl} \\ T_{cl} + \beta_2 (h - h_{cl}) & \text{for } h \geqslant h_{cl} \end{cases} \qquad \text{(II.44)}$$

In a particular case when $\beta_2 = 0$ the region above the cloud layer is isothermic with temperature $T_a = T_{cl}$. Depending upon the nature of the absorbent layer, the following particular cases of distribution of absorption according to altitude are of interest:

a) the entire thickness of the atmosphere is absorbent; the distribution of absorption is exponential;

b) the layer included between h_1 and h_2 is absorbent; the absorption in this layer is constant;

c) the layer included between h_1 and h_2 is absorbent; the distribution of absorption in this layer is parabolic. We shall examine these cases.

Case a. The whole thickness of the atmosphere is absorbent, and the distribution of absorption is exponential

$$\varkappa(\lambda, h) = \varkappa_0(\lambda) e^{-\frac{h}{H}}, \tag{II.45}$$

where $\kappa_0(\lambda)$ is the absorption at the level $h = 0$, H is the altitude of the uniform atmosphere. For the earth, this case corresponds to molecular absorption within the atmosphere.

In connection with the small contribution of that part of the atmosphere above the clouds we will assume, in order to simplify calculations, that $\beta_2 = 0$. Substituting (II.45) and (II.46) in (II.43) and carrying out a series of transformations, we obtain

$$\bar{T}_2[\tau(\lambda)] = T_{cl} - T_{ps} D_1(\tau) + \beta_1 H I_2(\tau, b), \tag{II.46}$$

where

$$D_1(\tau) = e^{-\tau}(1-\tau) - \tau^2 Ei(-\tau),$$

Ei is an exponential integral function;

$$I_2(\tau, b) = 2\int_0^1 a \int_1^b \frac{e^{-\frac{\tau z}{\sqrt{1-a^2}}}}{z}\, dz\, da, \tag{II.47}$$

$$b = e^{-h_{cl}/H}.$$

The functions $D_1(\tau)$ and $I_2(\tau, b)$ are shown in Tables 3 and 4 of the Appendix. The computation $I_2(\tau, b)$ was carried out on a calculating machine.

The resultant brightness temperature, averaged in accordance with the visual disk of the planet, for a smooth surface in this case equals

$$\bar{T}b\,[\tau(\lambda)] = T_{e0}I_1(\tau, \varepsilon) - T_{ps}D_1(\tau) + T_{c1} + \beta_1 H I_2(\tau, b). \tag{II.48}$$

Case b. The layer of finite thickness is absorbent. The absorption is constant according to altitude. /39

$$\varkappa(\lambda, h) = \begin{cases} \varkappa_0(\lambda) \text{ for } h_1 \leqslant h \leqslant h_2 \\ 0 \quad \text{ for } h < h_1 \,\&\; h > h_2. \end{cases}$$

Assuming also

$$h_{c1} > h_2 \text{ or } h_{c1} < h_1$$

we obtain

$$\bar{T}_2\,[\tau(\lambda)] = T_2 - T_1 D_1(\tau) + \frac{T_1 - T_2}{\tau} D_2(\tau), \tag{II.49}$$

where T_1 and T_2 are the temperatures of the atmosphere at the lower and at the upper boundaries of the layer,

$$D_2(\tau) = \frac{1}{3}\left[2 - e^{-\tau}(2 - \tau + \tau^2) - \tau^3 Ei(-\tau)\right].$$

Functions $D_2(\tau)$ are shown in Table 3 of the Appendix.

Case c. The layer of finite thickness is absorbent. The distribution of absorption is parabolic

$$\varkappa(h, \lambda) = \begin{cases} \varkappa_0(\lambda)\left[1 - \left(2\,\frac{h - h_m}{\Delta h_0}\right)^2\right] \text{ for } h_m - \frac{\Delta h_0}{2} \leqslant h \leqslant h_m + \frac{\Delta h_0}{2} \\ 0 \text{ for } h < h_m - \frac{\Delta h_0}{2} \,\&\; h > h_m + \frac{\Delta h_0}{2}, \end{cases}$$

where h_m is the altitude of maximum absorption, $\kappa_0(\lambda)$ is the absorption at altitude h_m, Δh_0 is the thickness of the layer at the level at which the absorption decreases to zero. Under earth conditions this case corresponds to absorption within the cloud layer or within the ionosphere. Designating $2\,\frac{h-h_m}{\Delta h_0} = y$ and carrying out a series of transformations, we obtain

$$\overline{T}_2[\tau(\lambda)] = I_3(\tau, T_m, \beta\Delta h_0), \qquad \text{(II.50)}$$

where

$$\dot{I}_3(\tau, T_m, \beta\Delta h_0) = \frac{3}{2}\tau\int_0^1 \frac{a}{\sqrt{1-a^2}} F(a)\,da, \qquad \text{(II.51)}$$

$$F(a) = \int_{-1}^{1}\left(T_m + \beta\,\frac{\Delta h_0}{2}\,y\right)(1-y^2)\,e^{-\frac{\tau}{2\sqrt{1-a^2}}\left[1-\frac{3}{2}y\left(1-\frac{y^2}{3}\right)\right]}\,dy,$$

$$\tau = \int_0^{\infty} \varkappa(h)\,dh = \frac{2}{3}\varkappa_0\Delta h_0. \qquad \text{(II.52)}$$

Here T_m is the temperature of the layer at the level of maximum absorption. /40
The functions $I_3(\tau, T_m, \beta\Delta h_0)$ have also been computed on a calculating machine and are shown in Table 5 of the Appendix.

The relationships shown above may be utilized for the interpretation of the results of measurements of Venus with radiotelescopes incapable of resolving details of the distribution of brightness temperature, and measuring only brightness temperature averaged in accordance with the visual disk of the planet. As indicated earlier, an increase in the resolving capability, necessary for the investigation of the distribution of radiobrightness along the Venus disk, may be achieved through the utilization of a radiointerferometer. In radiointerferometer investigations, a measured quantity characterizing the distribution of radiobrightness is a visibility function F(β). We will examine the relationship between the visibility function and the physical parameters of the planet. We will perform this examination without calculation of absorption in the atmosphere of Venus, assuming that the measurements are carried out through the window of transparency.

Interferometric visibility functions of a source having the form of a disk are defined in general form by the relationship

$$F(\beta) = \frac{\int_0^1 \cos 2\pi\beta x \int_0^{\sqrt{1-x^2}} T_b(x, y)\,dy\,dx}{\int_0^1 \int_0^{\sqrt{1-x^2}} T_b(x, y)\,dy\,dx}, \qquad \text{(II.12)}$$

where T_b (x, y) is the distribution of brightness temperature along the disk.

The value of the parameter β was clarified above on page 20.

For an equally bright disk

$$F_0(\beta) = \frac{J_1(2\pi\beta)}{\pi\beta} = \Lambda_1(2\pi\beta), \quad \text{(II.53)}$$

where J_1 and Λ are Bessel functions. Since such a type of visibility function is well known [18] and its calculation is carried out with the aid of generally available tables (see for example [100], it would seem convenient, in analogy to [261], to express the visibility function of a disk of non uniform brightness in the form

$$F(\beta) = F_0(\beta) + \Delta F_T(\beta) + \Delta F_p(\beta). \quad \text{(II.54)}$$

Here $\Delta F_T(\beta)$ is an *increment required by the dissimilarity of brightness temperature* over the disk of the planet, generated by the non-isothermality of the radiating medium, $\Delta F_p(\beta)$ is an increment required by the dissimilarity of the brightness temperature along the disk, and connected with the dependence of the radiating capability on polarization.

Let us carry out the calculation $\Delta F_T(\beta)$. Let us examine two types of /41
distribution of temperature of a radiating medium: central-symmetric change of temperature from the center to the edge of the visual disk and central-asymmetrical distribution with a decrease in temperature from the equator toward the poles. In summarizing the two indicated temperature distributions, one may obtain a distribution of a more complex nature. For the illumination of $F_0(\beta)$, and to obtain immediately the desired quantity $\Delta F_T(\beta)$, in a function describing the distribution of temperature, we introduce normalizing coefficients which exclude the constant component. In connection with this obtaining, negative temperatures indicates only that the resultant temperature of the sum of the uniformly bright disk and the observed distribution are less than the temperature of the uniformly bright disk.

a) Centrosymmetric Changes in Temperature from the Center to the Edge

1) Linear changes in temperature of the type $(1 - \frac{3}{2}a)$, where a is a varying polar coordinate. The component $\Delta F_T(\beta)$ is a visibility function of such distribution equal to

$$\Delta F_T(\beta) = H(\beta),$$

where

$$H(\beta) = \frac{1}{4}\left[\Lambda_1(2\pi\beta) - \frac{12}{\pi}\int_0^1 \cos(2\pi\beta x)x^2 \operatorname{arcsch} x dx\right]. \qquad \text{(II.55)}$$

The function $H(\beta)$ is presented in the form of a graph in Figure II.4.

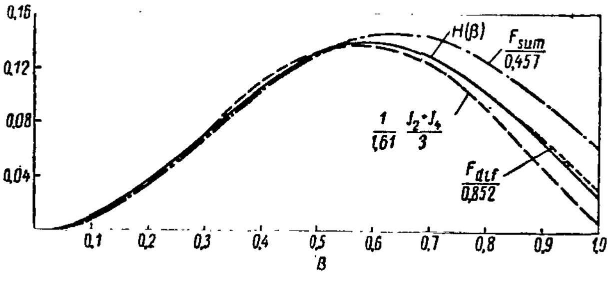

Figure II.4. Calculated Corrections to the Visibility Function for Nonuniform Distribution of Temperature.

2) Distribution of the type $[1 - (n + 1)\ \theta^{2n}]$. The component $\Delta F_T(\beta)$ of a visibility function of such distribution is the sum of Bessel functions of even order. /42
For n = 1

$$\Delta F_T(\beta) = \frac{1}{3}[J_2(2\pi\beta) + J_4(2\pi\beta)]. \qquad \text{(II.56)}$$

Three types of central asymmetry in temperature distribution, representing different forms of temperature decrease from the equator to the poles, are also examined.

b) Centroasymmetric Distribution with a Decrease in Temperature from the Equator to the Poles

1) Distribution of the form $(-\frac{1}{2}\cos\zeta)$. Here ζ is the angle of the observed point from the pole.

For this distribution

$$\Delta F_T(\beta) = -\frac{4}{\pi}\int_0^1 \cos 2\pi\beta x \int_0^{\sqrt{1-x^2}} \sqrt{x^2+y^2}\cos 2[\zeta - (\Phi - \chi)]dydx,$$

where $(\Phi - \chi)$ is the angle between the effective base and the axis of the planet. This expression is reduced to the form

$$\Delta F_T(\beta) = \frac{1}{3}H(\beta)\cos 2(\Phi - \chi). \qquad \text{(II.57)}$$

2) Distribution with parabolic decrease of temperature toward the pole of the form $(1/4 - y^2)$. Here y is the distance of the observed point from the equator in fractions of the radius of the planet. Taking into consideration that

$$\frac{1}{4} - y^2 = \frac{1}{4} - \theta^2 \cos^2 \zeta = \frac{1}{4} - \frac{\theta^2}{2}(1 + \cos 2\zeta),$$

we obtain

$$\Delta F_T(\beta) = \frac{1}{3}[J_2(2\pi\beta) + J_4(2\pi\beta)]\left[1 + \frac{1}{2}\cos 2(\Phi - \chi)\right]. \qquad \text{(II.58)}$$

3) Distribution with linear decrease of temperature from the equator to the pole of the form $(4/3\pi - |y|)$. For this case comparative simple Fourier transformations are obtained only for the equatorial and polar directions: /43

$$\left.\begin{aligned} \Delta F_T^{e}(\beta) &= \frac{4}{\pi}\left[-\frac{\frac{\sin 2\pi\beta}{2\pi\beta} - \cos 2\pi\beta}{(2\pi\beta)^2} + \frac{F_0(\beta)}{3}\right], \\ \Delta F_T^{p}(\beta) &= \frac{4}{3\pi}\left\{2\pi\beta\int_0^1 (1-x^2)^{3/2}\sin(2\pi\beta x)\,dx + [F_0(\beta) - 1]\right\} \end{aligned}\right\} \qquad \text{(II.59)}$$

In intermediate directions, with sufficient accuracy,

$$\Delta F_T[\beta, (\Phi - \chi)] = \Delta F_{sum} + \Delta F_{dif}\cos 2(\Phi - \chi),$$

where

$$\Delta F_{sum} = \frac{1}{2}(\Delta F_T^{p} + \Delta F_T^{e}),$$
$$\Delta F_{dif} = \frac{1}{2}(\Delta F_T^{p} - \Delta F_T^{e}).$$

In the interval $0 < \beta < 0.9$ of the function $[J_2(2\pi\beta) + J_4(2\pi\beta)]$, ΔF_{sum} and ΔF_{dif} is similar to $H(\beta)$ and may be approximated by the last function with a constant multiplier:

$$\frac{1}{3}[J_2(2\pi\beta) + J_4(2\pi\beta)] \cong 1{,}61H(\beta),$$
$$\Delta F_{sum} \cong 0{,}457H(\beta),$$
$$\Delta F_{dif} \cong 0{,}852H(\beta).$$

The accuracy of this approximation is seen in Figure II.4 where all of these functions are shown.

Considering the indicated approximation and keeping in mind that the visibility function of the indicated distribution is a linear combination of the visibility functions comprising these elements, we may reduce the resultant visibility function to the form

$$\Delta F_T(\beta) = H(\beta)\,[\Delta + \delta \cos(\Phi - \chi), \qquad (II.60)$$

which is convenient for comparison with experimental data. Δ and δ are generalized characteristics of temperature distribution. The relationship of these characteristics to the parameters which now directly interest us are shown in Table II.1 for four forms of temperature distribution. These parameters are $T_e - T_0$ which is the difference of temperatures on the equatorial limb and in the center of the disk, denoting a change of temperature along the equator, and $T_e - T_{pol}$ which is the difference in temperatures in the equatorial and polar parts of the limb denoting central asymmetry and darkening toward the poles.

TABLE II.1 /44

No.	Distribution of temperature on the disk	$T_e - T_0$	$T_e - T_{pol}$	T_0
1	$T = T_0 + \theta(T_e - T_0) - \cos^2\zeta(T_e - T_{pol})$	$-(3/2\,\Delta - \delta/2)\overline{T}$	$\delta \cdot \overline{T}$	$(1 + \Delta)\overline{T}$
2	$T = T_0 + \theta(T_e - T_0) - y^2(T_e - T_{pol})$	$-(3/2\,\Delta - 3/4\,\delta)\overline{T}$	$1{,}25\,\delta \cdot \overline{T}$	$(1 + \Delta - 0{,}189\,\delta)\overline{T}$
3	$T = T_0 + \theta^2(T_e - T_0) - y^2(T_e - T_{pol})$	$-1{,}21\,(\Delta - 1/2\,\delta)\overline{T}$	$1{,}25\,\delta \cdot \overline{T}$	$(1 + 0{,}62\,\Delta)\overline{T}$
4	$T = T_0 + \theta(T_e - T_0) - \|y\|(T_e - T_{pol})$	$-3/2\,(\Delta - 0{,}562\,\delta)\overline{T}$	$1{,}17\,\delta \cdot \overline{T}$	$(1 + \Delta - 0{,}064\,\delta)\overline{T}$

V.S. Troitskiy [90] showed that with a lack of central symmetry of distribution of brightness temperature, the integrated radio frequency radiation of a planet must be in part linearly polarized.

In a general case of central asymmetry, the value of polarization p is determined by the relationship

$$p = \frac{\frac{1}{\pi}\int\limits_0^1\int\limits_0^{2\pi} aE(a,\gamma)\,T(a,\gamma)\cos 2\gamma\,d\gamma\,da}{2\overline{T}_b}. \qquad (II.61)$$

where E(a, γ) is a distribution of radiation capability on the visible disk, determined by (II.30) and (II.32), T (a, γ) is the temperature distribution, $\overline{T}_b$ is the brightness temperature, averaged in accordance with the visible disk. /45

For asymmetry of the form $\frac{1}{2}$ cos ζ, the polarization of the integrated radiofrequency radiation is equal to

$$p = \delta \cdot P(\varepsilon). \qquad \text{(II.62)}$$

The function P (ε) is presented in the form of a graph in Figure II.5.

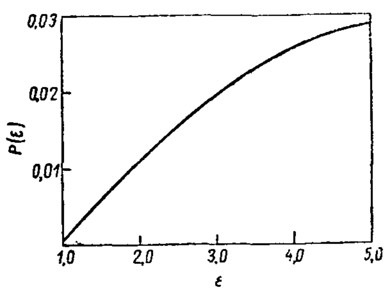

Figure II.5. Polarization of the Integrated Radiofrequency Radiation of the Planet as a Function of the Dielectric Constant of the Surface Material.

In the case when the polar regions are colder than the equatorial regions, the polarization component must be oriented along the equator of the planet.

The calculation F_0 (β) + ΔF_p (β) was carried out by Heiles and Drake [182] and Kuz'min and Clark [61]. The most detailed results of the calculation are presented in the form of a table in [63].

3. Theoretical Premises of Radar Planetary Investigations

The development in recent years of radar astronomy is still another prospective method of investigating Venus.

In contrast to radio astronomy, which involves the radio frequency radiation of celestial bodies themselves, the basis of radar astronomy lies in the investigation of reflected radiation of these bodies, which are subject to the influence of direct radiation from a radio transmitting apparatus especially utilized for these purposes.

In radar astronomy, as in ordinary radar, two methods of operation are utilized: the impulse method and the method of continuous radiation.

In measurement by the impulse method the planet is periodically irradiated by short impulses, the length of which are significantly shorter than the interval between them. The reception of the reflected signals is carried out in the interval between impulses radiated by the transmitting apparatus.

When reflected by a spherical planet, the signal in the general case is stretched both in time and in frequency.

Stretching in time is caused by the finite speed of propagation of electro-magnetic oscillations and by the depth of the reflecting body in the line of sight. An examination of this effect is more conveniently carried out under the impulse method of operation. It is apparent that the first signal registered at the receiver is the radiation reflected from a point on the surface of the planet closest to the earth observer. This point (see Figure II.6) is usually called the "point of initial contact". In time t after the beginning of the reflected signal impulse, the received energy will depend upon reflection of points of the surface of the planet, located at distance $\frac{ct}{2}$ along the line of sight beyond the point of initial contact. It is apparent that these points lie on a circle, the center of which is located on a straight line passing through the point of initial contact and the center of the sphere. It is not difficult to show that the angle θ, from under which the circle is visible from the center of the planet, is connected with the delay time of the reflected signal t by the simple relationship /46

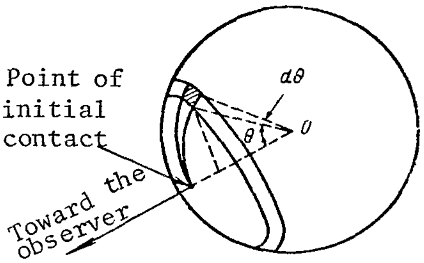

Figure II.6. The Geometry of the Reflection of an Impulse Signal from a Spherical Planet.

$$t = \frac{2R}{c}(1 - \cos\theta), \qquad \text{(II.63)}$$

where R is the radius of the reflecting layer of the planet.

The greatest delay $t_m = \frac{2R}{c}$ will take place for radiation reflected from points located on the limb of the planet (θ = 90°).

It is apparent that in making a selection by time it is possible to isolate radiation from various areas of the planet and by this method investigate separately these areas. The resolving capability of this selection is limited by the finite length of the impulse τ of the radio transmitting apparatus. It is apparent that the energy of the signal received during the interval dt = τ (see Figure II.7) corresponds to the reflection from a ring (Figure II.6) with an angular width dθ, which is determined by the relationship

$$dt = \frac{2R}{c}\sin\theta d\theta. \qquad \text{(II.64)}$$

The method of continuous radiation is characterized by a very narrow band of frequencies of the radiated signal, and is limited only by the technical instability of the transmitter and of the heterodyne oscillator of the receiver. Therefore the most important application of this method is the measurement of the frequency spectrum of the reflected signal. The latter differs from the spectrum of the radiated signal due to Doppler shift of the average frequency, caused by progressive motion of the planet relative to the observer with radial velocity v, and is equal to /47

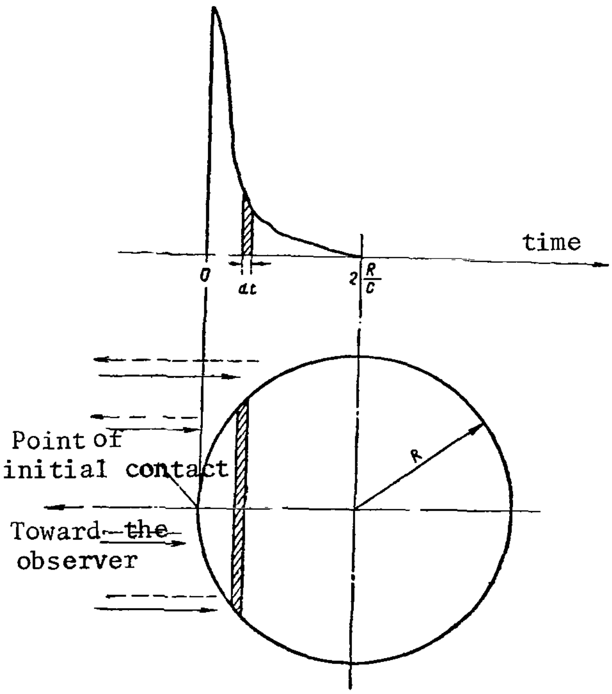

Figure II.7. Schematic Representation of Radiation Impulse Stretching Upon Reflection by a Spherical Planet.

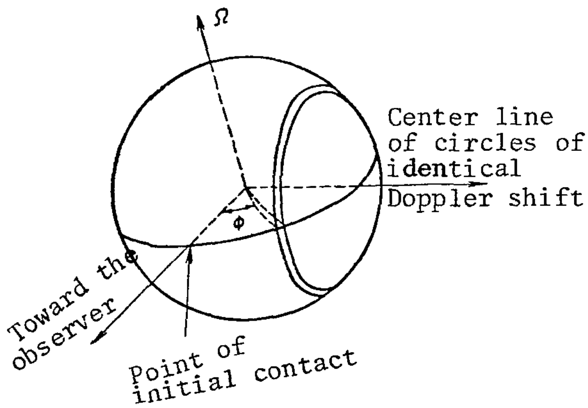

Figure II.8. The Geometry of the Reflection of Continuous Radiation from a Rotating Spherical Planet.

$$\Delta\nu = \frac{2v}{c}\nu_0, \qquad \text{(II.65)}$$

where ν_0 are the frequencies of the radiated signal and the Doppler broadening, caused by planetary rotation.

It may be shown that circles on the surface of a sphere are the loci of points having an identical linear speed on the line /48 of sight to the observer and therefore also an identical Doppler shift. The centers of these circles are located on a straight line passing through the center of the sphere perpendicular to the plane formed by the direction to the observer and by the axis of rotation of the planet (Figure II.8). To an observer these circles appear as segments of straight lines parallel to projections of the rotation axis on the plane of the figure (Figure II.9).

With the apparent angular speed Ω of planetary rotation relative to the projection of the rotation axis on the plane of the figure, each such segment, which is located at distance x from the rotation axis of the planet, has a supplemental linear speed on the line of sight equal to $2x\Omega$ and a supplemental Doppler shift in frequency

$$\delta\nu = \frac{2x\Omega}{c}\nu_0. \qquad \text{(II.66)}$$

The combination of selection by time delay, which permits the isolation of a signal reflected from a defined ring on the visible disk of the planet (Figure II.6), with selection by frequency, which permits the isolation of reflection from a band which is located at a defined distance from the rotation axis of the planet (Figure II.9) makes possible the resolution on the planetary disk of relatively small areas corresponding to the intersection

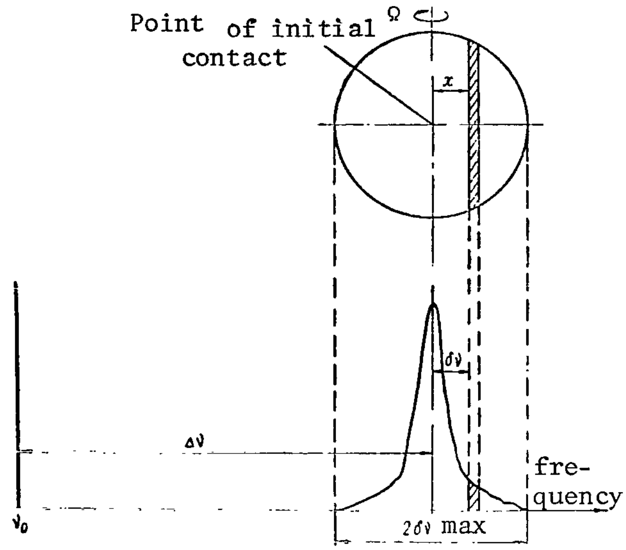

Figure II.9. A Schematic Representation of Doppler Frequency Broadening During Reflection from a Rotating Planet.

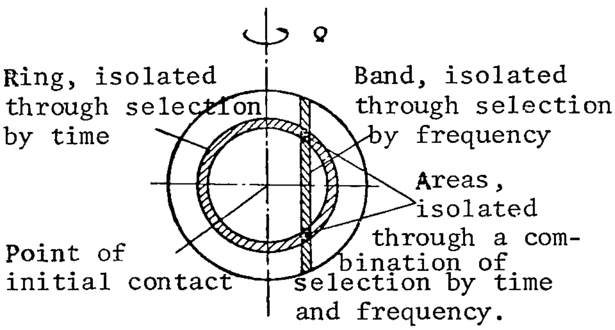

Figure II.10. Schematic Representation of Increased Resolution Obtained Through Selection by Time and Frequency.

of the indicated ring and band (Figure II.10). In this way it is possible to study indirectly the distribution of reflected characteristics on the planetary disk with the aid of earth antennas, with pattern widths too great to carry out these measurements directly. A /49 significant short-coming of this method of increasing angular resolution is ambiguity. The intersection of the ring with the band results in two areas (see Figure II.10), the separation of which without additional selection is not considered possible.

Full Doppler broadening of the spectrum of radiation reflected from the entire planet comprises

$$B=\frac{4R\Omega}{c}\nu_0, \qquad \text{(II.67)}$$ /50

where R is the radius of the planet.

In operating with the method of continuous radiation, reception of the reflected signal occurs simultaneously with primary radiation. In this connection, for the elimination of interference from the transmitter in this case it is necessary to either carry out reception and transmission with different antennas sufficiently displaced from each other, or to work in a quasi-continuous mode, radiating high frequency oscillations for a sufficiently long period of time required for the propagation of radiation from the earth to Venus and return. The transmitter is then switched off during the time of reception.

Elements of the rotation of Venus are some of the parameters which may be defined through radar measurement.

The angular speed Ω of the apparent planetary rotation relative to the projection of the rotation axis on the plane of the figure may be defined from the relationship (II.67) with the aid of measurement of the broadening of the spectrum B of the reflected signal.

However, if the reflecting surface is sufficiently smooth (i.e., the characteristic dimension of unevenness is small in comparison with the wavelength at which the investigation is carried out), the basic part of the primary radiation is reflected from a comparatively small (equal to the first zone of Frenel) central part of the planet; reflection from the edges of the disk is very small. Therefore measurements of the full width of the spectrum of the reflected signal demand a significant excess of signal over noise, which has not yet been achieved in the majority of contemporary measurements. This difficulty may be overcome through the combination of spectral measurements with the above mentioned measurements of distribution of reflection according to distance. It must be emphasized however that a single measurement, no matter how accurate, permits the determination of only the apparent speed of planetary rotation for the earth observer, but does not answer the question of direction of rotation and of orientation of rotation axis. The indicated parameters may be defined as a change in the apparent speed of rotation of Venus in due time [55, 255] only from extended radar measurements.

The apparent rotation of Venus for an earth observer is the result of the true rotation of the planet and, besides this, motions of the earth in relation to Venus. A calculation of the second component, which may be computed theoretically, shows that if the rotation of Venus is direct, it may be /51
expected that the apparent speed of its rotation will be maximum near the inferior conjunction and will decrease on both sides of it. With retrograde rotation the apparent speed of rotation of Venus must be at a minimum at the inferior conjunction.

In Figure II.11 there is shown the calculated dependence of the apparent speed of rotation of Venus on the date of the inferior conjunction for various periods and on direct and indirect rotation of the planet. Curve 2 corresponds to so-called synchronous rotation, when the period and direction of the characteristic rotation of Venus around the axis and its orbital revolution around the Sun are identical, and therefore the planet always presents the same side to the Sun. Curve 1 corresponds to another particular case when Venus does not rotate at all relative to the stars and its apparent rotation is caused only by the relative movement of the earth and Venus. The significance of the remaining curves is clear from the drawing.

Figure II.11 was plotted for a case when the axis of rotation of Venus is perpendicular to the plane of its orbit. With other orientations of the axis of rotation, curves representing the dependence of the apparent speed of rotation on the date become non-symmetrical. An analysis of this asymmetry /52
makes it possible to determine both the orientation of the axis, and therefore also the orientation of the poles of the rotation of Venus.

The relief of the surface of the planet is another parameter of Venus which is being determined from radar measurements.

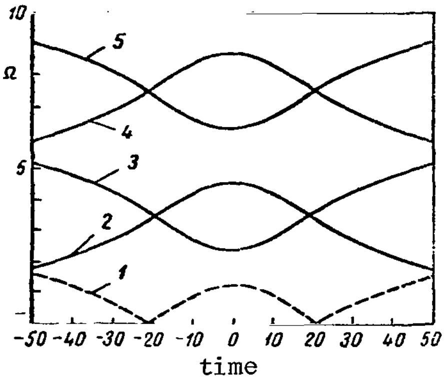

Figure II.11. Calculated Apparent Angular Speed of Rotation of Venus (in units 10^{-7} radians/sec) as a Function of Time to the Inferior Conjunction of the Planet, in Earth Days, for the Following Cases:
1) there is no rotation of Venus around the axis,
2) rotation is direct with a period of 225 days,
3) rotation is retrograde with a period of 225 days,
4) rotation is direct with a period of 100 days,
5) rotation is retrograde with a period of 100 days.

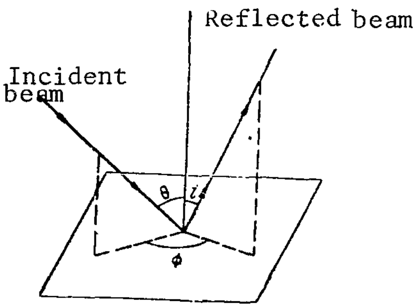

Figure II.12. Geometry of Diffused Reflection of Radiation.

The intensity of the reflected radiation P depends upon the direction of the reflected beam relative to the incident beam. In a general case P is a function of three angles: the angle of incidence θ, the angle of reflection i, and the difference of azimuths Φ of the incident and reflected beams (see Figure II.12).

$$P = P_0 F(\theta, \Phi, i). \qquad \text{(II.68)}$$

Here P_0 is a certain constant, defining the absolute value of reflection capability, and F(θ, Φ, i) is a function of diffusion expressing relative change of reflection with a change of direction of the incident and reflected beams. The finding of this function is possible either theoretically on the basis of an examination of the mechanism of diffusion of a reflecting surface having a fixed statistically determined surface unevenness, or by means of a corresponding experiment.

For radar location of Venus from the earth, measurements F(θ, Φ, i) are carried out only for a particular case of reflection in the direction of the incident beam (i = θ, Φ = 0). Here the measured value is the function of reflection F (θ), which in this manner becomes a particular case of the function of diffusion F (θ, Φ, i).

For a dull uniformly diffusing surface, the function of reflection is described by Lamberts Law

$$F(\theta) = \cos^2 \theta. \qquad \text{(II.69)}$$

For a surface reflecting in accordance with Lommel-Zilinger's Law

$$F(\theta) = \cos \theta. \qquad \text{(II.70)}$$

For a surface consisting of a large number of sufficiently large (in comparison with wavelength) randomly inclined flat mirror-reflecting parts, the reflection is called quasi-specular, and the function of reflection has a maximum when $\theta = 0$ and decreases sharply upon an increase in θ. A widely /53
utilized method of statistical description of such a surface is that taken in [165]. Assuming that the true surface differs from the mean, and that the inclinations are random, then deviations in altitude from the mean level are characterized by normal distribution with root mean square deviation h_0. The horizontal scale of the unevenness of the surface is given by the auto-correlation function $\rho(d)$. In examining two forms of this function, the Gaussian is

$$\rho(d) = \exp\left[-\frac{1}{2}\left(\frac{d}{d_0}\right)^2\right] \tag{II.71}$$

and the exponential is

$$\rho(d) = \exp\left[-\frac{d}{d'}\right]. \tag{II.72}$$

The function of reflection of such a surface consisting of a dielectric may be presented in the form

$$F(\theta) \propto \frac{\exp\left[-\frac{1}{2}\left(\frac{\theta}{\theta_0}\right)^2\right]}{\cos^4\theta}, \tag{II.73}$$

where $\theta_0 = h_0/d_0$ is the mean inclination of the reflecting surface for Gaussian distribution of slopes or

$$F(\theta) \propto [\cos^4\theta + C\sin^2\theta]^{-3/2}, \tag{II.74}$$

where

$$C = \left[\frac{d'\lambda}{4\pi h_0^2}\right]$$

When C is large (which applies to this examination) the equation (II.74) may be reduced to the form

$$F(\theta) \propto \left[\frac{1}{1 + (C-2)\theta^2 - \left(\frac{C-5}{3}\right)\theta^4}\right]^{3/2}. \tag{II.75}$$

A comparison carried out by Evans [165] of the function of reflection described by (II.73 - II.75), with experimental curve F(θ) of the quasi-specular component of lunar reflection on radiowaves, reveals the close conformity of the experiment with the calculation for the exponential auto-correlation function when C = 102 and 32 on waves of 68 and 3.6 cm, respectively. Many forms of the earth's surface are also described by exponential laws [181]. /54

Insofar as the exponential law of distribution is concerned, the root mean square inclination is not a parameter which uniquely describes the characteristics of the surface. A more significant characteristic is the actual distribution of inclinations of the surface f(θ) in relation to the average surface. Then, as Rea and others [274] have shown in an approximation of geometric optics

$$F(\theta) \propto \frac{8\pi f(\theta)}{\cos\theta}. \tag{II.76}$$

The inclinations must be taken with consideration for conformity with the area of their projections on the average surface; it is necessary to fulfill the conditions

$$\int f(\theta)\sin\theta d\theta = 1. \tag{II.77}$$

A function of reflection may be experimentally determined on the basis of measurement data of the intensity distribution of reflection by distance, or by measurement data of the frequency spectrum of the reflected signal.

As has already been pointed out above, selection by distance makes it possible to isolate radiation from a ring concentric to the point of initial contact (Figure II.6). Further, with the aid of (II.64) it is not difficult to plot with the measured tentative spectrum P(t) the angular spectrum P'(θ) of the reflection from the rings irradiated by an impulse with duraction τ. The area of these rings equals

$$\Delta S = \pi R c\tau, \tag{II.78}$$

i.e., does not depend upon the position of the ring on the sphere. Therefore the angular spectrum P'(θ) characterizes the reflection not only of the rings of identical depth; it is also a characteristic of the reflection of a single element of the surface, i.e., it is (after normalization) the desired function of reflection F(θ).

The relationship of the function of reflection with the frequency spectrum of the reflected signal P(ν) is determined by the relationship [128]

$$P(\nu) \propto \pm \int_0^{\sqrt{\delta\nu_m^2 - \nu^2}} \frac{P(\theta)}{\sqrt{\delta\nu_m^2 - \nu^2 - y^2}} dy, \tag{II.79}$$

where

$$\theta = \arcsin\left[\frac{\sqrt{\nu^2 + y^2}}{\delta\nu_m}\right],$$

ν is the frequency, $\delta\nu_m$ is half of the width of the spectrum of the reflected /55
signal from limb to limb.

The inverse transformation may be carried out with the aid of Abel's integral equation, which gives

$$P(\theta) \propto \cos\theta \int_{\delta\nu_m \sin\theta}^{\delta\nu_m} \frac{P'(\nu)}{\sqrt{\nu^2 - \delta\nu_m^2 \sin^2\theta}}\, d\nu. \tag{II.80}$$

The dielectric characteristics of the material of the surface of the planet are the next parameters of Venus which may be evaluated on the basis of radar measurement data.

The coefficient of reflection ρ of the surface consisting of a dielectric with a complex dielectric permittivity $\varepsilon = \varepsilon' + j\varepsilon''$ is determined by the relationship

$$\rho = \left(\frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}\right)\left(\frac{\sqrt{\varepsilon_*} - 1}{\sqrt{\varepsilon_*} + 1}\right). \tag{II.81}$$

Here $\varepsilon_* = \varepsilon' - j\varepsilon''$ is a complex conjugate quantity with dielectric permittivity ε.

In a case when $\varepsilon'' \ll \varepsilon'$ (low electrical conductivity), which occurs for the Moon and for the majority of earth-like surfaces, (II.81) leads to the well known form

$$\rho = \left(\frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}\right)^2. \tag{II.82}$$

From this, knowing ρ, it is not difficult to calculate

$$\varepsilon = \left(\frac{1 + \sqrt{\rho}}{1 - \sqrt{\rho}}\right)^2. \tag{II.83}$$

The quantity ρ may be determined through measurement data of the effective cross-section of the radar reflection

$$S_e = g\rho\pi R^2, \tag{II.84}$$

where πR^2 is the area of the geometric cross-section of the planet, g is the coefficient of the direction of the reflected radiation.

The effective cross-section of the radar reflection S_e is determined directly from measurement. Transforming the well known radar equation (see for example [14])

$$P_0 = P_{tr}\frac{GAS_e}{(4\pi r^2)^2}, \tag{II.85}$$

where P_{tr} is the transmitter power, G is the amplification factor of the transmitting antenna, A is the effective area of the receiving antenna, r is the distance to the reflecting object, and considering that the total reflected power is /56

$$P_0 = \int_0^{\tau+2\frac{R}{c}} P(t)\,dt \tag{II.86}$$

or

$$P_0 = \int_{-\delta\nu_m}^{+\delta\nu_m} P(\nu)\,d\nu, \tag{II.87}$$

we obtain

$$S_e = \frac{(4\pi r^2)^2}{P_{tr}GA}\int_0^{\tau+2\frac{R}{c}} P(t)\,dt = \frac{(4\pi r^2)^2}{P_{ti}GA}\int_{-\delta\nu_m}^{+\delta\nu_m} P(\nu)\,d\nu. \tag{II.88}$$

Usually the results of measurement of S_e are expressed in fractions of the geometrical area of a cross-section of the planet

$$\sigma_e = S_e/\pi R^2.$$

The directional coefficient g of the reflected radiation depends upon the statistical characteristics of the reflecting surface and in a general case is defined by the relationship

$$g = \frac{4\pi \int_0^{\pi/2} F(\theta) \sin\theta d\theta}{\int_0^{\pi/2} \int_0^{\pi/2} \int_0^{2\pi} F(\theta, i, \Phi) \sin\theta \sin i d\Phi di d\theta}. \tag{II.89}$$

It has already been mentioned above however that the function of diffusion F (θ, Φ, i) cannot be determined through earth experiment. Therefore it is necessary to limit the approximate evaluation of the g parameter, based upon the results of a determination of the statistical characteristics of the reflecting surface and measurement of the indices of reflection.

For a sphere that is smooth in relation to wavelength, and which provides specular reflection, g = 1.

Daniels and Winter revealed [140, 332] that if the surface of a planet consists of a great number of flat areas, large in comparison with wavelength, but inclined toward the sphere, and providing quasi-specular reflection, the directional coefficient of the reflected signal is equal to $g = 1 + \bar{\alpha}^2$, where $\bar{\alpha}$ is the mean angle of inclination. For small values of $\bar{\alpha}$, $g \cong 1$ may be accepted as a sufficiently close approximation.

For a surface that is rough on the wavelength scale and which diffuses reflected radiation in accordance with Lambert's Law, the directional coefficient g = 8/3 [177]. /57

In processing the results of radar measurements of Venus it is the usual practice to describe the reflected signal as the sum of two components: the quasi-specular component, caused by mirror reflection of flat areas of planetary regions close to earth, and the diffused component, caused by a uniformly diffusing part of the surface which is rough on the wavelength scale. With such a combination, the full effective cross-section σ_e of reflection of the planet may be presented in the form

$$\sigma_e = g_{sp}\rho(1 - a_d) + g_d \rho a_d, \tag{II.90}$$

where a_d is the relationship of parts of the planetary disk providing diffused reflection to the full cross-section of the planet; g_{sp} and g_d are coefficients of the direction of specular and diffused reflection.

Designating by b_{sp} and b_d the respective ratios of the energy of the specular and diffused component to the total power of the reflected signal, and considering that $b_{sp} + b_d = 1$, and accepting in agreement with the above that $g_{sp} = 1$ and $g_d = 8/3$ and carrying out simple transformations, we obtain

$$\rho = \left(b_{sp} + \frac{3}{8} b_d\right) \sigma_e. \tag{II.91}$$

The values b_{sp} and b_d are determined from experiment.

Also it is possible to calculate further

$$\left.\begin{array}{c} a_{sp} = \frac{b_{sp}\sigma_e}{\rho} \\ \text{and} \\ a_d = \frac{3}{8}\frac{b_d\sigma_e}{\rho} \end{array}\right\}. \qquad \text{(II.92)}$$

The division into quasi-specular and diffused components is carried out on the basis of an analysis of the reflective function, which is conveniently plotted on the scale

$$\lg F(\theta) = f[1 + \lg\cos\theta].$$

It is apparent that on this scale the reflective function of the diffusion component will have a form of a straight line with the angular inclination equal to minus 2. By extrapolation of this straight line it is possible to obtain the reflective function of the diffusion component F (θ) in the whole range of angles θ from 0 to 90°. The quantity b_d is determined from the relationship /58

$$b_d = \frac{\int_0^{90°} F_d(\theta)\sin\theta d\theta}{\int_0^{90°} F(\theta)\sin\theta d\theta}. \qquad \text{(II.93)}$$

All of the remaining reflection is considered to be quasi-specular and $g = g_{sp} = 1$ and $b_{sp} = 1 - b_d$ and accepted for it.

The indicated dual component model, which does not take into account components of the reflected signal caused by intermediate reflection between the quasi-specular with $g_{sp} = 1$ and the diffusion with $g_d = 8/3$, and having therefore a directional coefficient $1 < g < \frac{8}{3}$, is considered relatively coarse. Conditionally, we shall call the indicated intermediate area the area of scattered reflection. With the calculation of scattered reflection the relationships (II.91) and (II.92) are transformed to the form

$$\rho = \left(b_{sp} + \frac{3}{8}b_d + \frac{1}{g_s}b_s\right)\sigma_e, \qquad \text{(II.94)}$$

where g_s and b_s are the coefficients of direction and relative energy of the scattered reflection, respectively.

In connection with the fact that $g_s > 1$, it is apparent that the value of the coefficient of reflection ρ, and therefore also the dielectric permittivity ε, calculated with the component of scattered reflection, must be less than that obtained from the coarser dual component model.

The relative area of parts of the planetary disk responsible for the reflection of various components may be determined from the relationship

$$\left.\begin{aligned} a'_{sp} &= \frac{b_{sp}\sigma_e}{\rho} \\ a &= \frac{3}{} \frac{b_d\sigma_e}{} \\ a_s &= \frac{1}{g_s}\frac{b_s\sigma_e}{\rho} \end{aligned}\right\}. \qquad (II.95)$$

The entire examination cited above was conducted under the assumption of planetary atmospheric transparence and is correct therefore only for those radiowave bands for which this assumption is applicable.

Radar measurements of planets also permit the measurement of the distance to them and thus the determination of the astronomical unit. /59

From these measurements themselves, the radius of the planetary reflecting layer may be determined. Actually, the distance to a planet may be determined by two methods:

a) Directly, by measurement of the time of propagation of the radar signal from the transmitter to the planet and back to the receiver. In this case the measured value represents the distance from the observer to the point of initial contact of the reflecting layer.

b) From the velocity of planetary motion along the solar orbit, measured on the basis of Doppler frequency shift of the reflected signal (with a correction for motion of the observer due to rotation of the earth and its orbital motion). In this case the measured value represents the distance to the center of the planet.

By comparing the results of distance measurements utilizing the two indicated methods, it is possible to determine the radius of the reflecting layer of the planet.

CHAPTER III

THE RESULTS OF RADIO PHYSICAL MEASUREMENTS OF VENUS

1. The results of Radio Astronomic Measurements of Venus.

a) The Spectrum of Radio Frequency Radiation.

The first observations of characteristic radio frequency radiation of Venus were accomplished in 1956 by Mayer, McCullough, and Sloanaker in the 3-cm wave band on the 15 meter radiotelescope of the Naval Research Laboratory of the USA [227]. The choice of the 3-cm wave band was brought about by a compromise between the decrease of radio frequency flux density of the planet with a longer wave, on the one hand, and the lack at the time of radiotelescopes suitable for work in the millimeter range, and by deterioration in the sensitivity of radiometers at shorter waves, on the other hand. The results of these measurements proved to be quite unexpected: it was revealed that the brightness temperature of Venus, averaged by the visible disk of the planet, is equal to approximately 600°K, i.e., it exceeds by more than two times the radiometric temperature 235°K obtained earlier in the infrared range [259, 295].

However the result obtained could not be immediately interpreted, for neither the area responsible for the radiation obtained nor the mechanism of this radiation was known.

As mentioned above, the spectrum is one of the most important characteristics of the mechanism of radio frequency radiation.

The first attempt at measurement of the spectrum of radio frequency radiation of Venus was also undertaken by Mayer and others [227]. However, the measurements carried out by them on the longer 9.4 cm wave proved to be quite rough. Two observations were made in all, and the brightness temperatures of Venus, averaged in accordance with the visible disk of the planet, were determined to equal 430 and 740°K, respectively, with errors of ±50%. /61

Just as approximate were the measurements of Gibson and McEwan [19, 167], accomplished in 1958 on the shorter 8.6 mm wave. In the author's conclusion, the value of the brightness temperature of Venus, averaged by the visible disk, is probably located between 250 and 570°K with an average value of 410°K, i.e., this value equally agrees both with infrared measurement data and with the results of measurements by Mayer and others in the 3-cm wave band. Sagan [278] interpreted these data in the same way having concluded in 1960 that the measurements of Gibson and McEwan were in close agreement with the measurements of Mayer and others; he also concluded that the lower value of the average value for brightness temperature on the 8.6 mm wave was caused by insufficient accuracy of measurement due to a great amount of apparatus noise.

More exact measurements in the 8 mm wave band were carried out in 1959 by Kuz'min and Salomonovich [52] at the Physical Institute of the Academy of Sciences of the USSR. Using a 22-meter radiotelescope, considered to be the largest of those suitable for work in the millimeter wave band, they revealed that the brightness temperature of Venus in the 8 millimeter band, averaged by the visible disk of the planet, is positively and significantly lower than on the 3.15 cm wave.

In the course of the next several years, measurements of brightness temperature of Venus were carried out intensively at a series of radio-astronomic stations of the USSR and the USA in a wide band of wavelengths from 1 mm to 70 cm. The results of these measurements are condensed in Table III.1. The spectrum of radio frequency radiation from the side of Venus not illuminated by the Sun has been plotted in Figure III.1 according to data from this table, i.e., brightness temperature, averaged by the non-illuminated side of the planet, is shown as a function of wavelength.

The approximate constancy of the brightness temperature of Venus in the wavelength band from 2 to 20 cm approximately, and the significant decrease in brightness temperature on shorter waves, are the most characteristic features of the spectrum.

Of interest in obtaining data concerning the composition of the atmosphere of Venus is the shift of part of the spectrum from higher brightness temperatures in the centimeter range toward lower brightness temperatures in the millimeter range. Especially interesting is the form of the shift of the portion of the spectrum near 1.35 cm wavelength, which corresponds to a water vapor absorption line. With the presence of water vapor in the atmosphere of Venus there must be a "gap" on this wave in the spectrum of planetary radio frequency radiation.

First measurements of brightness temperature of Venus on the 1.35 cm wave, carried out by Gibson and Corbett [169], did not reveal any kind of spectrum peculiarity on this wave. More detailed measurements on a series of /70
waves near 1.35 cm, carried out by Welch and Thornton [329] and Drake and others [155], with an accuracy of measurement evaluated by the authors at 5%, revealed that the radiation spectrum of Venus near the water vapor absorption line is smooth.

Analogous measurements by Barrett and Staelin [110, 310] point to a change in the form of the spectrum in the observed area from day to day with the appearance on specified days of the "gap" on the 1.35 cm wave. A second series of measurements made by Gibson [170] is also an indication in favor of a "gap" in the spectrum of this wave. Latest measurements by Staelin and Reifenstein [311], carried out in 1966 on waves 1.18; 1.28; 1.35; 1.42 and 1.58 cm, revealed brightness temperatures of 400 ± 40°K, 418 ± 42°K, 436 ± 44°K, 451 ± 45°K and 477 ± 60°K, showing again in the same manner that the radio frequency radiation spectrum of Venus near the water vapor absorption line is smooth. Changes themselves in the form of the spectrum from day to day did not exceed measurement errors. Thus the results of contemporary measurements of the spectrum of radio frequency radiation of Venus near the water vapor absorption line are contradictory and this interesting question awaits further experimental investigation.

TABLE III.1.*

λ, см	$\bar{T}_{b♀}$, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. reference
0,1—0,14	318 ± 35° K	Ø 200", Mount Palomar	F. Low	1965	[220]
0,32	300^{+84}_{-54}	Ø 4,9 м, Univ. of Texas, USA	C. W. Tolbert A. W. Straiton	1964	[321, 322]
0,33	292^{+40}_{-30}	Ø 4,6 м, Aerospace Corp. USA	E. Epstein	1965	[160]
0,34	320 ± 50	Ø 4,6 м, Aerospace Corp. USA	E. Epstein	1966	[161]
0,4	360 ± 90	Ø 22 м, Physical Institute of Academy of Sciences, USSR	A.G. Kislyakov A.D. Kuz'min A.Ye.Salomonovich	1961	[35, 63]
0,43	350^{+50}_{-30}	Ø 3 м, Naval Research Laboratory, USA	C. R. Grant H. H. Corbett J. E. Gibson	1963	[176]
0,43	330^{+80}_{-60}	Ø 4,9 м, Univ. of Texas, USA	C. W. Tolbert A. W. Straiton	1964	[321, 322]
0,8	405 ± 80	Ø 22 м, Physical Institute of Academy of Sciences, USSR	A.D. Kuz'min A.Ye.Salomonovich	1960	[52, 63]
	382 ± 75	same as above	A.D. Kuz'min A.Ye.Salomonovich	1962	[54, 63]

*Tr. Note. Commas indicate decimal points.

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Table III.1. (continued)

λ, cm	$T_{b\varrho}$, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. references
	394 ± 30	same as above	Yu.N.Vetukhnovskaya A.D. Kuz'min B.G. Kutuza A.Ye.Salomonovich	1963	[17, 63]
0,835	395 ± 60	Ø 3 м, Univ. of California, USA	D. D. Thornton W. J. Welch	1964	[319]
	390 ± 45	same as above	W. J. Welch D. D. Thornton	1965	[329]
0,85	380^{+72}_{-34}	Ø 8,5 м, Lincoln Univ., Lab. Massachusettes Institute of Technology, USA	V. L. Lynn M. L. Mecks M. D. Sohigian	1964	[222]
0,86	410 ± 160	Ø 3 м, Naval Research Lab., USA	J. E. Gibson R. J. McEwan	1959	[19, 167]
	410^{+30}_{-20}	same as above	J. E. Gibson	1963	[168]
0,86	353	Ø 8 м, Evan-Knight Corp., USA	J. Copeland W. C. Tyler	1964	[139]
0,86	375 ± 58	Ø 4,9 м, Univ. of Texas, USA	C. W. Tolbert A. W. Straiton	1964	[321, 322]
0,926	430 ± 24	Ø 8,5 м, Lincoln Lab., Mass. Inst. of Tech., USA	A. H. Barrett D. Staelin	1965	[110, 310]
0,97	412 ± 55	Ø 3 м, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]

Tr. Note: Commas indicate decimal points.

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Table III.1. (continued)

λ, *см*	$T_{b♀}$, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. references
1,01	463 ± 32	∅ 8,5 *м*, Lincoln Univ., Lab. Mass. Inst. of Tech., USA	A. H. Barrett D. Staelin	1965	[110, 310]
1,16	495 ± 50	∅ 3 *м*, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]
1,18	395^{+75}_{-55}	∅ 8,5 *м*. Lincoln Lab., Mass. Inst. of Tech., USA	D. H. Staelin A. H. Barrett B. R. Kusse	1964	[309]
	428 ± 20	same as above	A. H. Barrett D. H. Staelin	1965	[110, 310]
1,24	451 ± 53	∅ 3 *м*, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]
1,28	450 ± 23	∅ 8,5 *м*, Lincoln Lab., USA	A. H. Barrett D. H. Staelin	1965	[110, 310]
1,35	520 ± 40	∅ 3 *м*, Naval Research Lab., USA	J. E. Gibson H. H. Corbett	1963	[169]
	435	same as above	J. E. Gibson H. H. Corbett	1965	[170]
1,35	540 ± 40	∅ 3 *м*, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]

Tr. Note: Commas indicate decimal points.

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Table III.1. (continued)

λ, cm	$\overline{T}_{b♀}$	Radiotelescope Institution	Observers	Year pub.	Biblio. references
1,37	404 ± 28	∅ 8,5 м, Lincoln Lab., USA	A. H. Barrett D. H. Staelin	1965	[110, 310]
1,42	572 ± 82	same as above	A. H. Barrett D. H. Staelin	1966	[310]
1,45	595 ± 50	⍉ 3 м, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]
1,6	534 ± 60	⍉ 22 м, Physical Institute of Academy of Sciences, USSR	Yu.N. Vetukhnovskaya A.D. Kuz'min B.Ya. Losovskiy A.Ye. Salomonovich	1963	[17]
1,65	560 ± 51	⍉ 3 м, Univ. of California, USA	W. J. Welch D. D. Thornton	1965	[329]
2,07	500 ± 70*	∅ 15 м, Naval Research Lab., USA	T. P. McCullough J. W. Boland	1964	[231]
3,15	560 ± 73	∅ 15 м, Naval Research Lab., USA	C. H. Mayer T. P. McCullough R. M. Sloanaker	1958	[227]
	550 ± 70	same as above	C. H. Mayer T. P. McCullough R. M. Sloanaker	1963	[230]
3,3	542 ± 85*	∅ 22 м, Physical Institute of the Academy of Sciences, USSR	V.P. Bibinova A.D. Kuz'min A.Ye. Salomonovich I.V. Shavlovskiy	1962	[13]

Tr. Note: Commas indicate decimal points.

/65

Table III.1. (continued)

λ, см	$\bar{T}_b$ ♀, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. references
	575±30	Ø 22 м, Physical Institute of the Academy of Sciences, USSR	Yu.N. Vetukhnovskaya A.D. Kuz'min A.Ye. Salomonovich	1963	[17]
3,37	575±60	Ø 15 м, Naval Research Lab., USA	L. E. Alsop J. A. Giordmaine C. H. Mayer C. H. Townes	1958	[103]
3,75	660±60° K*	Ø 26 м, Univ. of Michigan USA	A.D. Kuz'min W. Dent	1966	[65]
5,2	590±50	Ø 22 м, Physical Institute of the Academy of Sciences, USSR	Yu.N. Vetukhnovskaya A.D. Kuz'min R.L. Sorochenko	1966	
9,4	580±160	Ø 15 м, Naval Research Lab., USA	C. H. Mayer T. P. McCullough R. M. Sloanaker	1958	[227]
9,6	660±75	Ø 22 м, Physical Institute of the Academy of Sciences, USSR	A.D. Kuz'min A.Ye. Salomonovich	1961	[53, 63]
10,0	553±60	same as above	Yu.N. Vetukhnovskaya A.D. Kuz'min A.Ye. Salomonovich	1965	[63]

Tr. Note: Commas indicate decimal points.

/66

Table III.1. (continued)

λ, cm	$\overline{T}_{b♀}$, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. references
10,0	590±50	Ø 26 м, National Radio-astronomical Observatory, USA	F. D. Drake	1962	[152]
	584±14	same as above	F. D. Drake	1964	[154]
10,2	605±85	Ø 25 м, Naval Research Lab., USA	C. H. Mayer T. P. McCullough R. M. Sloanaker	1960	[229]
10,3	630	Ø 22 м, Physical Institute of Academy of Sciences, USSR	Yu.N. Vetukhnovskaya	1965	[63]
10,6	580±60	Interferometer 2 × 27 m Calif. Inst. of Tech., USA	A.D. Kuz'min B. Klark	1965	[61]
10,7	580±60	same as above	B. G. Clark C. L. Spencer	1964	[136]
11,3	605±33	Ø 65 м, Australia	K. I. Kellerman	1965	[197]
13	712±80	Nancy, France	A. Boischot M. Ginat I. Kazes	1963	[115]
18	596±100	Interferometer Calif. Inst. of Tech., USA	B. G. Clark C. L. Spencer	1964	[136]
21	600	Ø 18 м, Harvard Univ. USA	A. E. Lilley	1961	[219]

* Measurements were carried out near dichotomy.

Tr. Note: Commas indicate decimal points.

/67

Table III.1. (continued)

λ, см	$\bar{T}_{♀}$, °K	Radiotelescope Institution	Observers	Year pub.	Biblio. references
21	674±70	Nancy, France	A. Boischot M. Ginat I. Kazes	1963	[115]
21	616±100	Interferometer Calif. Inst. of Tech., USA	B. G. Clark C. L. Spencer	1964	[136]
21,2	591±30° K	∅ 76 м, Jodrell Bank, England	R. D. Davies D. W. Williams	1966	[142]
21,3	590±30	∅ 65 м, Australia	K. I. Kellerman	1965	[197]
21,4	528±33	∅ 90 м, National Radio-astronomical Observatory, USA	F. D. Drake	1964	[154]
31,2	510±50	∅ 65 м, Australia	K. I. Kellerman	1965	[197]
40	400±60	∅ 90 м, National Radio-astronomical Observatory, USA	F. D. Drake	1964	[154]
48,4	505±100	∅ 65 м, Australia	K. I. Kellerman	1965	[197]
70	518±40	∅ 300 м, Puerto Rico	H. E. Hardebeck	1965	[180]

Tr. Note: Commas indicate decimal points.

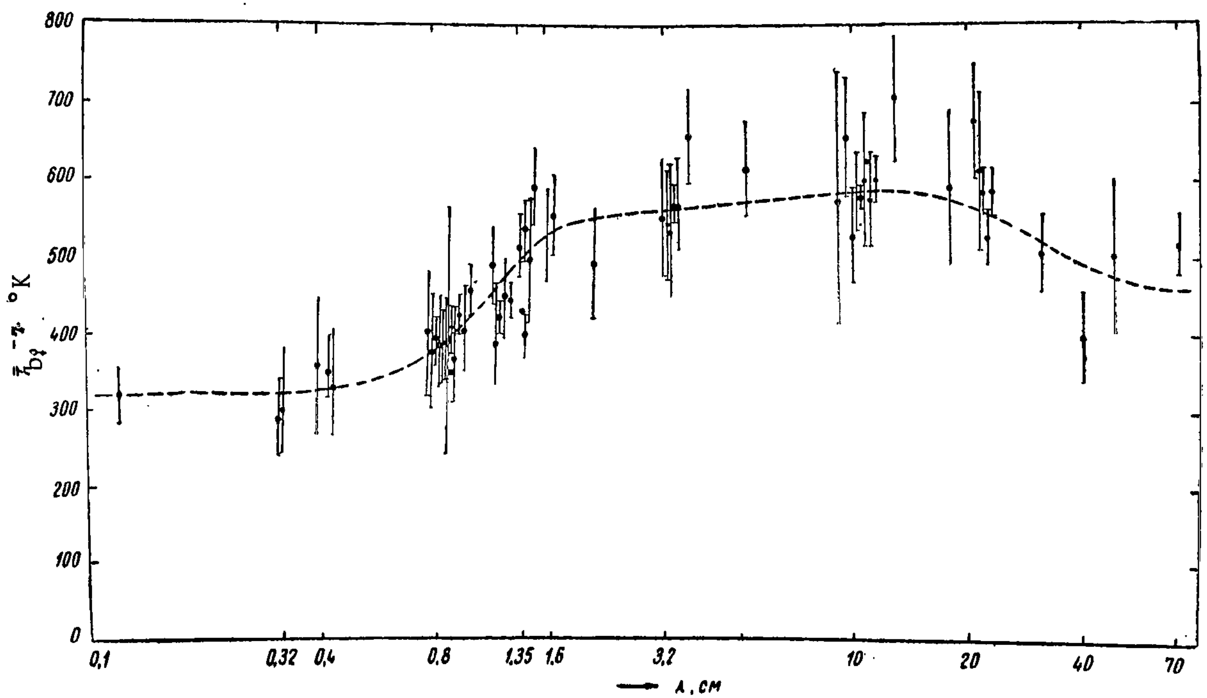

Figure III.1. Spectrum of Brightness Temperature, Averaged by the Visible Disk of the Planet, of the Side of Venus not Illuminated by the Sun.

A subsequent interesting but not yet confirmed detail of the spectrum is the decrease in brightness temperature, averaged by the visible disk of the planet, in the decimeter wave band range. This decrease was detected by Drake [154] from measurements carried out by him on 21 and 40 cm waves. However Drake himself remarks that in connection with the possible incidence of solar radio frequency radiation on side lobes of the antenna, the result obtained by him must be regarded with caution. Later measurements by Kellerman [197] on the 31 and 48 cm waves and by Hardebeck [180] on the 70 cm wave also are indications in favor of a decrease of brightness temperature of Venus in this band.

It seems to us that in order to carry out measurements in the decimeter wave band, which is very important for an understanding of the physics of Venus, one must apply interference methods of observation, which permit the exclusion of the influence of celestial radio frequency noise.

b) Phase Variation of Brightness Temperature

The measurements of Venus, the results of which were discussed above, were carried out near the inferior conjunction of the planet and refer therefore to the side of the planet not illuminated by the Sun. Near the superior conjunction, when Venus turns its illuminated side toward the earth, its /71 solid angle is approximately 40 times less than at the inferior conjunction.

In connection with the fact that the radiation flux density of the planet is proportional to the solid angle, direct measurement of the radio frequency radiation of Venus near the superior conjunction is a very difficult task. Therefore evaluations of brightness temperature of the illuminated side of Venus were first accomplished through extrapolation of the results of observations carried out in periods when only a small part of the planet was illuminated by the Sun.

The resolving power of contemporary radiotelescopes is still insufficient for the measurement of the differences in brightness temperature of separate parts of the planetary disk. Therefore the measured value is the brightness temperature, averaged by the visible disk of the planet. If the brightness temperature of the illuminated and non-illuminated sides of the planet are different, one would expect a "phase variation", i.e., dependence of brightness temperature, averaged by the disk, on planetary phases, i.e., on the relative area of the illuminated part of the disk.

Such measurements, carried out in 1959 by Kuz'min and Salomonovich [52] on the 8 mm wave from the inferior conjunction to dichotomy revealed an increase in brightness temperature, averaged by the disk, during an increase in a relative area of the illuminated part of the disk.

The presence of brightness temperature phase variation of Venus in the millimeter wavelength band was confirmed by measurements performed in 1961 by Kuz'min and Salomonovich [54] and Copeland and Tyler [139] in the 8 mm band and Kislyakov, Kuz'min and Salomonovich [35] in the 4 mm band. However, Grant

Corbett and Gibson [176], having carried out observations at the same time on the 4.3 mm wave, did not detect phase variation.

Epstein [160], having carried out measurements on the 3.3 mm wave in 1964, obtained results which, depending upon the method of their processing, attest either to the lack of phase variation, or even to an anti-phase variation, i.e., a decrease in brightness temperature of radio frequency radiation of Venus in proportion to an increase of the fraction of the planetary disk illuminated by the Sun. In the second case a dependence of $\overline{T}_{b♀}$ on Φ is approximated by Epstein by the analytical relationship

$$\overline{T}_{b♀}(\Phi) = \underset{\left(\substack{+40 \\ -30}\right)}{297} - \underset{(\pm 5)}{23} \cos (\Phi - \underset{(\pm 10^\circ)}{0^\circ}), \ ^\circ\mathrm{K}.$$

In 1960 Mayer, McCullough and Sloanaker [228] also reported the presence of phase variation in the brightness temperature of Venus on the 3.15 cm and 10 cm waves. In agreement with later and more accurate measurements by these /72 authors on the 3.15 cm wave [230] extending over a period of three and one half months after the inferior conjunction, the dependence of brightness temperature, averaged by the visible disk, on phase variation is approximated by the relationship

$$\overline{T}_{b♀}(\Phi) = \underset{(\pm 5)}{621} + \underset{(\pm 6)}{73} \cos (\Phi - \underset{(\pm 22)}{11{,}7^\circ}), \ ^\circ\mathrm{K}.$$

Due to the fact that only the absolute value of the phase angle Φ of the illumination of Venus by the Sun is recorded in astronomical reference books, and in order to avoid ambiguity here and further on, Φ is entered with a positive sign up to the inferior conjunction and with a negative sign after the inferior conjunction

The extrapolation of this relationship to the superior conjunction reveals a brightness temperature of the illuminated side of Venus equal to 694°K.

On the 10 cm wave the dependence of brightness temperature of Venus on phase was studied by Drake [154] near the inferior conjunctions of 1961 and 1962. His results may be approximated by the relationship

$$\overline{T}'_{b♀}(\Phi) = \underset{(\pm 6)}{622} \pm \underset{(\pm 12)}{41} \cos (\Phi - \underset{(\pm 9^\circ)}{21^\circ}), \ ^\circ\mathrm{K}.$$

The corresponding extrapolation to the superior conjunction reveals a brightness temperature of the illuminated side of Venus equal to 663°K.

An attempt to measure the phase dependence of $\overline{T}_{b♀}(\Phi)$ on the 21 cm wave was undertaken by Davies and Williams [142], from September 7, 1962 to February 18, 1963. In the phase angle interval from $\Phi = 94°$ to $\Phi = -78°$ they obtained an antiphase variation, approximated by the relationship

$$\overline{T}_{b♀}(k) = \underset{(\pm 5)}{597} - k\underset{(\pm 34)}{39},\ °K.$$

Here k is the relative area of the visible disk of the planet illuminated by the Sun. However, due to the fact that the variable component is of the same magnitude as measurement error, the authors conclude that the phase variation is small: the peak-to-peak amplitude of the variable component $\overline{T}_{b♀}$ is evaluated by them at less then 12°K, i.e., the amplitude of the phase variation is less than 1%.

However, not long ago the results of measurements carried out by Gibson and Corbett [170] were published; they studied the dependence of $T_{b♀}$ on phase on the 1.35 cm wave, the line of water vapor absorption. The data they obtained indicates the independence of $\overline{T}_{b♀}$ of phase in the phase angle range from 135 to -130° and the rapid rise of $\overline{T}_{b♀}$ after dichotomy roughly propor- /73 tional to the relative area of that part of the visible disk illuminated by the Sun.

The authors present the results of their measurements in the form

$$\overline{T}_{b♀}(k) = 430 - 440°\text{K for } k < 0{,}19$$
$$T_{b♀}(k) = 320 + k600°\text{K for } 0{,}19 < k < 0{,}6.$$

The data cited above concerning brightness temperatures of the side of Venus illuminated by the Sun on the 3.15 and 10 cm waves were obtained through extrapolation and therefore cannot be considered sufficiently accurate. For a determination of this parameter, direct measurements near the superior conjunction of the planet when its illuminated side is turned toward the earth are required.

The first direct measurement of the brightness temperature of Venus near the superior conjunction was carried out by Drake [153], who obtained on the 10 cm wave in the phase angle intervals $\Phi = 14 - 37°$ the brightness temperature averaged by the disk, of

$$\overline{T}_{b♀\circ} = 610 \pm 55°\text{K}.$$

This value below 663°K, obtained by extrapolation from the results of his own measurements [154] carried out only near the inferior conjunction, and correct within measurement errors, coincides with the brightness temperature of the non-illuminated side of Venus according to the data of Drake himself [154] and amounts to 584 ± 15°K on the same wave.

In 1964 analogous measurements of Venus in the 10 cm wave band were carried out independently by Kuz'min [62] and Kellerman [197]. Kuz'min, in making measurements by comparison with reference source 3C48, obtained brightness temperatures for Venus, averaged by the visible disk of the planet, near the inferior and superior conjunctions equal to 580 ± 10°K and 550 ± ± 20°K*, respectively. According to Kellerman's data, corresponding temperatures are 605 ± 30°K when $\Phi = -137°$ and 629 ± 30°K when $\Phi = -45°$.

Thus direct measurements have shown that the difference in brightness temperatures of the illuminated and non-illuminated sides of Venus on the 10 cm wave do not exceed 5%, i.e., the amplitude of the phase variation is not greater than 2.5%.

An attempt at direct measurement of $\overline{T}_{b♀}$ near the superior conjunction was undertaken by Dickel [147] on the 3 cm wave band. The author maintains /74 that the difference in temperatures of the illuminated and the non-illuminated sides of Venus is equal to 120°K. An analytic interpretation utilizing the method of least squares of experimental points, cited in [147], reduces to phase dependence of the form

$$\overline{T}_{b♀}(\Phi) = 649 + 37\cos(\Phi - 20°),\ °K,$$

i.e., the amplitude of the variable component is 1.6 times less than the author maintains. However even this result is applicable only for three (of a total number of 31) isolated points, and after their exclusion the amplitude of the variable component decreases by almost double and the phase dependence is approximated by the relationship

$$\overline{T}_{b♀}(\Phi) = 639 + 20\cos(\Phi + 7°),\ °K.$$

In connection with the internal contradiction of these results and their lack of agreement with data obtained from measurements of Mayer and others [230], the question of phase dependence of brightness temperature of Venus in the 3 cm wave band remains open.

In the millimeter band, direct measurements of brightness temperature of the illuminated side of Venus were carried out by Basharinov, Vetukhnovskaya, Kuz'min, Kutuza and Salomonovich [9, 63] near the superior conjunction in 1963. Jupiter was used as a reference source for which a brightness

* The cited error characterizes only random errors and does not take into account absolute errors in the determination of the flux density of 3C48, which may reach 10%.

temperature of 140°K was taken. On the 8 mm wave, brightness temperatures, averaged by the disk, were obtained as follows: 435 ± 80°K, 462 ± 65°K and 440 ± 70°K at phase angles -43°, -14° and 13°, respectively. A comparison of these data with results of measurement carried out near the inferior conjunction in 1962 with the same reference source leads to a phase dependence of brightness temperature of Venus approximated by the relationship

$$\overline{T}_{b\text{♀}}(\Phi) = 427 + 42(\Phi - 43^\circ),\ ^\circ\mathrm{K}$$

confirming the phase variation $\overline{T}_{b\text{♀}}$ revealed earlier [52] in the millimeter wave band.

An interesting characteristic of the detected phase dependence is the shift of its minimum relative to the inferior conjunction. Kuz'min and Salomonovich [55] pointed out the possibility of utilizing this shift to determine the direction of rotation of Venus on its axis. Actually in the case of direct rotation (i.e., motion in the same direction as orbital motion) of Venus (see Figure III.2), the morning side of the planet is turned toward /75
the earth at eastern elongations, and the evening side at western elongations. In connection with the thermal inertia of the planet it may be expected that during eastern elongations the dark side of the disk has already cooled, and the illuminated side has not yet become fully warmed; during western elongations the dark side has not yet cooled, and at the same time the illuminated side has become warm. In summary, the brightness temperature of the planet, averaged by the visible disk, in identical areas of illumination of the part of the disk will prove to be lower for eastern elongations than for western. This leads to a shift in the moment of onset of the minimum in brightness temperature in the direction of the eastern elongations, i.e., before the inferior conjunction. In the case of retrograde rotation, the minimum of brightness temperature may be expected after the inferior conjunction.

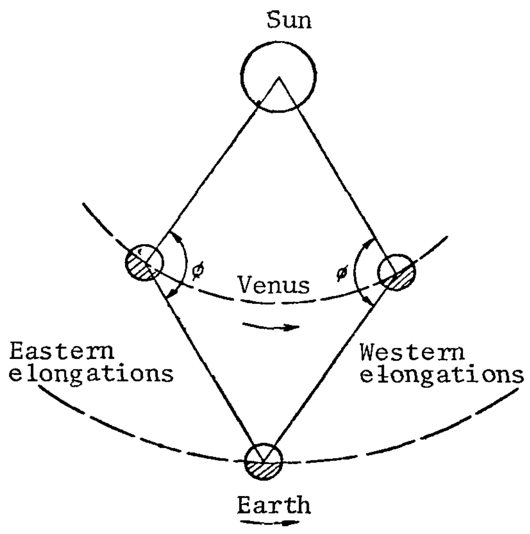

Figure III.2. Schematic Diagram Explaining the Method of Determination of the Direction of the Rotation of Venus from Radio Astronomic Observations (not drawn to scale).

Acquired experimental data points to a shift in the minimum in the direction of western elongations, which may attest to a retrograde rotation. It must be noted however that phase variation measurement accuracy is so far insufficient for an unambiguous resolution of the question concerning the direction of planetary rotation by these data alone.

c) Distribution of Radioluminescence /76

All of the measurements enumerated above have been carried out on radiotelescopes having a directional pattern width larger than the solid angle of Venus. In this connection the measured value is the integrated flux density of the radio frequency radiation of the planet or the brightness temperature, averaged in accordance with its visible disk. The brightness temperatures of Venus cited in Table III.1 and further in the text are defined in precisely this way. However, the assumption set forth that the source of the radio frequency radiation has the same angular dimensions as the visible disk of the planet is not clear. In addition, the described brightness temperature that is of direct interest for the determination of the physical characteristics of the planet, may in general depend on the planetocentric coordinates, i.e., may prove to be different for different parts of the visible disk.

In the determination of this dependence, measurements of the distribution of radioluminescence on the Venus disk are required. The accomplishment of such measurements demands very high resolving power, not yet achieved in radiotelescopes installed on earth. Therefore even with systems having at the present time the greatest resolving power it is possible to carry out now only qualitative measurements and only near the inferior conjunction of Venus. The first measurements of this type were carried out in 1962 by Korol'kov, Pariyskiy, Timofeyeva and Khaykin [42] and Clark and Spencer [136] on the 3.02 and 9.4 cm waves, respectively.

Korol'kov and others used the large Pulkovo radiotelescope having a knife edge pattern width in the horizontal cross-section of 1'.2 at the half power level. The measured value represented the width of the curved passage of Venus, from which the broadening caused by Venus was determined by comparison with the calculated directional pattern. The value of this broadening permitted the calculation of the angular dimensions of the reflecting layer and the character of the distribution of radioluminescence.

From the data obtained, it follows that on the 3 cm wave the radius of the radio frequency radiating area does not exceed 1.07 times the radius of the visible disk of Venus. The character of the distribution of radioluminescence best of all agrees with darkening of the edge of the planetary disk and clearly contradicts limb brightening.

Clark and Spencer carried out measurements using the interferometer method. The interferometer utilized consisted of two 27-meter parabolic antennas, deployed in an east-west direction at a distance of 490 m (5184 λ). With a change in the hour angle, a change in the effective length of the base was utilized. An insufficiency of experimental material prevented the definite /77 clarification of the character of radioluminescence distribution. A disk of uniform brightness, the diameter of which exceeds the diameter of the visible disk by 15%, and also a bright ring on the planetary limb from which 1/4 of the radio frequency radiation of the entire planet is emitted, were pointed out as possible distributions. The amplitudes of the spatial spectrum obtained do not agree with the distribution of radioluminescence corresponding to darkening of the edge of the disk or to uniform distribution of radioluminescence on the visible disk.

Thus the measurements accomplished gave qualitatively diverse results concerning the character of the distribution of radioluminescence on the Venus disk.

As has already been noted above, the resolving power of contemporary earth radiotelescopes is thus far insufficient for the examination of separate details on a planetary disk. Even during an observation from a distance of 10,000 km in the centimeter wave band with an antenna of moderate dimensions (about 1 m) it is possible to resolve areas corresponding approximately to 1/500 of the area of the visible planetary disk. In this connection it seems possible to detect directly the presence of darkening or brightening of the edge, the dependence of brightness temperature on solar illumination, and also to reveal areas of different radiation capability (for example seas and continents). Besides this, conducting observations beyond the limits of the earth's atmosphere raises the accuracy of spectroscopic examinations of the atmospheric composition of Venus, especially for gases present in earth's atmosphere (O_2, H_2O). Such an experiment with radiotelescopes installed on space probe Mariner-2, directed toward Venus, was carried out in the USA in 1962 [104, 105, 108].

It was assumed originally that measurements would be carried out on four waves, 4 and 8 mm and 1.35 and 1.9 cm, to obtain charts of the distribution of brightness temperature on the Venus disk. However, the experiment on Mariner-2 was carried out only on two waves in accordance with an abbreviated program; 1.35 and 1.9 cm. Due to a malfunction in the scanning system only three profiles of Venus were obtained. Five measurements on the dark side of the planet, eight along the terminator and five on the light side were accomplished. On the 1.9 cm wave the maximum temperature of the central profile (590°K) was essentially greater than the maximum temperature of the other two profiles taken near the edge of the planet (480 and 460°K). The value of this difference exceeds the random error of measurement, which consists of 5% in the author's evaluation, and also the expected effect of smoothing by the directional pattern, and is interpreted by the authors as a decrease in planetary brightness temperature toward the edge and in a direction perpendicular to the direction of scanning. A large systematic error is also possible.

On the second wave of 1.35 cm, the measurements were carried out with low accuracy (random error ±25%) due to low apparatus sensitivity. Maximum brightness temperatures of the central and edge profiles were determined to equal 400, 393 and 396°K, respectively. Thus a decrease in brightness temperature from the center to the edge was not detected, although on the shorter wave a stronger effect of darkening of the planetary edge was to be expected. It is possible that the lack of the edge darkening effect was caused by insufficient measurement accuracy.

More detailed measurements of the distribution of radioluminescence on the Venus disk were carried out by Kuz'min and Clark [61] in 1964 at the

Radiointerferometer Station Owens Valley of the California Institute of Technology on the 10.6 cm wave. The observations were carried out at various base lengths from 600 λ to 6,500 λ and at various base orientations.

The positional angle of the effective base of the interferometer is relative to the observed source and therefore the direction in which investigations of the distribution of radioluminescence are carried out depends on the orientation of the base of the interferometer and on the position of the source on the celestial sphere (see § II.1). As a result of this profiles of the planet in various directions were obtained during observations with various base orientations and with different hour angles of Venus. A comparison of the results obtained made it possible to investigate the central symmetry of the distribution of brightness temperature on the visible disk of the planet. The results of the analysis reveal that the distribution of brightness temperature on the visible planetary disk is centrally asymmetric: in the direction close to the perpendicular to the ecliptic, the edges of the disk are colder than the ecliptical edges of the disk and its central part. The centers of gravity of the revealed cold areas are conditionally called the "cold poles" of Venus. The locations of the poles determined in this manner are, in the ecliptical system of coordinates,

$$\lambda_p \cong 200^\circ \text{ and } \beta_p \cong 70^\circ; \quad \lambda_p \cong 20^\circ \text{ and } \beta_p \cong -70^\circ.$$

In the equatorial direction there is a tendency toward an increase in planetary brightness temperature from a point opposite the sun toward the equatorial limb. The maximum increase comprises 23%, however, within the limits of measurement error, a decrease of approximately 2% is even possible.

The radius of the radiating area has been determined to equal 6,060 ± ± 55 km, i.e., 0.99 ± 0.01 of the radius of the visible Venus disk.

d) Polarization /79

The first attempt to measure the polarization of the integrated radiofrequency radiation of Venus was undertaken by Mayer, McCullough and Sloanaker [227] on the 3.15 cm wave. Polarization could not be detected within the accuracy of measurement error.

In 1962, Seielstad, Morris and Radhakrishnan [292] in conducting measurements of the polarization of the radio frequency radiation of a series of discrete sources, also attempted to measure the polarization of the integrated radio frequency radiation of Venus on the 10.6 cm wave. Data from the observations at the Radiointerferometer Station Owens Valley of the California Institute of Technology revealed the presence of a polarized signal which comprises 0.6% of full intensity; the positional angle of the polarized component was 111°. However, the accuracy of measurements (± 1.1% of a degree of polarization and ± 54° of the positional angle) was so low that the authors themselves did not consider the data obtained by them to be reliable.

More productive results of measurements of the polarization of the integrated radiation of Venus were conducted on the same instrument by Kuz'min and Clark in 1964 [61]. The degree of polarization was measured on the 10.6 cm wave and equalled 0.8 ± 0.5%.

In 1964 Kuz'min and Dent [65] conducted measurements on the shorter 3.75 cm wave using the 26-meter University of Michigan radiotelescope. They revealed that the polarization of the integrated Venus radiation on this wave is less than 1%.

All of the data explained above are the results of measurements of the integrated polarization of the radio frequency radiation of the entire Venus disk. The measurement of the distribution of radioluminescence on the planet in polarized radiation has a great deal of significance in solving the cardinal problem for the physics of the planet concerning the nature of radio frequency radiation. Such measurements were conducted by Kuz'min and Clark [61] from May 25 to July 18, 1964 during the time of the investigations of Venus mentioned above with a high degree of resolution on the radiointerferometer of the California Institute of Technology.

The visibility function is represented by measured values of the interferometer in two polarizations: parallel to the effective base of the interferometer, F ||, and perpendicular to it, F ⊥. The results of these measurements are presented in Figure III.3. The Parameter β, the meaning of which was clarified on page 20, characterizes the spatial frequency of the interferometer. For further analysis and comparison of the results of measurement carried out under various conditions, approximations to the visibility function were determined through the method of least squares for each series of observations. The approximations were /80 generated by curves of the second order. For research into the dependence of the visibility function on polarization and on the positional angle of the base projection, the indicated approximation was made separately for the

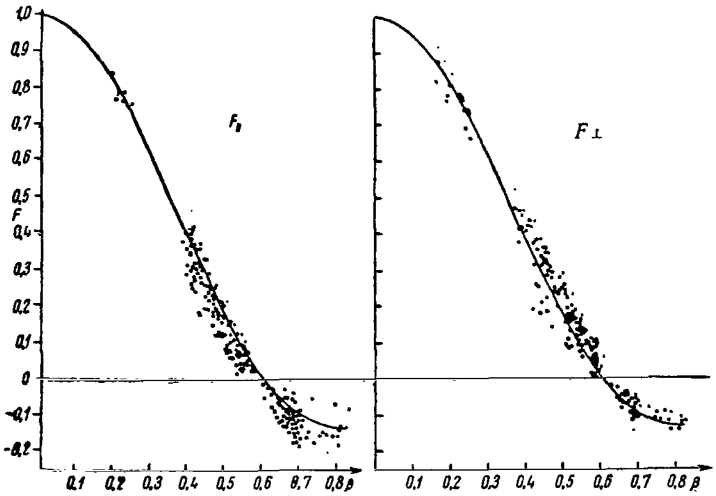

Figure III.3. The Results of Measurements of the Visibility Function of Venus in Polarizations Parallel F || and Perpendicular F ⊥ to the Effective Base of the Interferometer. The Visibility Function of a Uniformly Bright Disk equal to the Ephemeris Venus disk is shown by a Continuous Line.

polarizations parallel F || and perpendicular F | to the effective base of the interferometer and for negative (t < 0) and positive (t > 0) hour angles. The results are presented in Table III.2 in the form of discrete points approximating curves. In connection with the fact that the approximation was generated by a curve of the second order, the four points cited in Table III.2 are not mutually independent. Therefore the resulting error was also determined directly by dispersion. The positional angles of the effective base of the interferometer χ, determined from the relationship (II.14), are also cited in the table. For the visibility function of the uniformly small interval β in which the measurements were conducted, the linear dependence F on β with the angular coefficient 2.16 was obtained, corresponding to an inclination of the visibility function of the uniformly bright disk. The dependence F on hour angle t was approximated by a parabola.

e) Variations in Brightness Temperature /82

In 1961 Kuz'min and Salomonovich reported [53] the presence of variations in the brightness temperature of Venus on the 9.6 cm wave. Subsequent analysis [[63, 211] revealed that, due to an insufficient signal to noise ratio, in a majority of cases it was not possible to make an unambiguous determination of whether these variations were real or whether they were caused by insufficient measurement accuracy. However, on two days of observation* on April 4 and April 23, 1961, such high brightness temperatures were noted (1,000 - 1,500°K), that they could not be explained as accidental measurement errors.

Similar variations were not confirmed, however, by Drake's observations on the neighboring 10 cm wave. [152]. According to Drake's data, variations in brightness temperature do not exceed 7% for an eight minute average and 2% on the average for a whole day of observation.

The fact that the indicated disagreements are connected with differences in method of measurement cannot be excluded: Kuz'min and Salomonovich determined brightness temperatures from single passages, while the brightness temperatures obtained by Drake were averages for an eight minute interval and therefore did not contain information concerning more rapid variations.

Additional observations with characteristic times not longer than one minute are required to solve this problem.

The presence of variations in the radio frequency radiation of Venus were noted also in the measurements of Boischot and others [115] on the 13 and 21 cm waves and in measurements by Barrett and Staelin [110] in the region of the spectrum $\lambda = 1 - 2$ cm, reflecting a transition from high to low brightness temperatures. Recently Letfus [216] reported the presence of a correlation between variations of $\overline{T}_{b♀}$ on a 3.3 cm wave in accordance with measurements [13] and solar activity.

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* The observations were conducted for a period of 41 days.

f) Attempts at Observation of the Radio Frequency Radiation of Venus in the Decimeter Wavelength Band

The first publications concerning the reception of characteristic radio frequency radiation from Venus were made by Kraus [203, 204, 205] who reported his observations of the radiation from Venus on the 11 m wave. At the Observatory of the University of Ohio (USA) they registered an impulse type signal approximately one second and less in duration, which was attributed to radiation from Venus. A tendency toward an 11-day periodicity was also noted, on the basis of which Kraus [205] determined the rotation period of Venus to equal either 22^h17^m, or 13 days. However subsequent observations of the author and a reexamination of old results, which he conducted, revealed that the measurement results [203-205] were in error. Apparently the observed burst of radiation had an earth origin. /83

2. Results of Radar Measurements of Venus

Price and others [270] made the first attempt at radio location of Venus during the course of two days in February 1958. The measurements were conducted on 68 cm with the aid of the 26-meter antenna of the Lincoln Laboratory of the Massachusetts Institute of Technology (USA). Due to the low signal to noise ratio, the reflected signal was revealed only through statistical analysis. However of four series of observations subjected to this analysis, the signal apparently was revealed only in two of these. Subsequent measurements, conducted in the same laboratory [256], revealed that the astronomical unit was incorrectly determined. In this connection Pettengill [257], one of the authors of the work [270], reasoned that the signal obtained in 1958 was not a reflection from Venus but was caused by some kind of parasitic effect. Therefore one may not consider reliable the value of the effective cross-section of the radar reflection of Venus, which according to the data of this experiment is equal to a cross-section of the planet, i.e., is approximately 10 times larger than that obtained in subsequent measurements.

An attempt by Pettengill and Price [254] to conduct radar studies of Venus near the next inferior conjunction in 1959 also proved to be unsuccessful: the reflected signal was not detected.

Evans and Taylor [163], also having conducted radar studies of Venus in 1959 at the Radio Astronomic Station Jodrell Bank in England, reported the detection of a reflected signal exceeding the noise by 2.5 times and corresponding to an effective cross-section of reflection 0.5% and to an astronomic unit value coinciding with that obtained by Price and others [270], which proved to be in error.

The first successful radar measurements of Venus were conducted near the inferior conjunction in 1961 in the USSR by a group of colleagues of the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR under the leadership of the academician V.A. Kotel'nikov [43,44,202], in the USA at the Lincoln Laboratory of the Massachusetts Institute of

Technology by Pettengill and others [255] and at the Jet Propulsion Laboratory of the California Institute of Technology [225, 237, 325], and in England at the Radio Astronomical Observatory Jodrell Bank [317]. Basic data concerning these measurements, and also concerning measurements carried out near subsequent inferior conjunctions in 1962 and 1964,are presented in Table III.3. /86

In the course of these experiments the spectrum of the reflected signal, the effective cross-section of the radar reflection and its distribution with distance, and also signal propagation time and Doppler frequency shift were measured.

a) Frequency Spectrum of Reflected Radiation. Determination of the Parameters of the Rotation of Venus.

The frequency spectrum of the reflected radiation is one of the most important parameters measured in radar experiment which has facilited the generation of unique data concerning the parameters of the rotation of Venus.

The first measurements of the frequency spectrum of the reflected radiation of Venus were conducted in 1961 in the USSR at the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR by V.A. Kotel'nikov and others [43, 44] and in the USA at the Jet Propulsion Laboratory of the California Institute of Technology [237] and at the Lincoln Laboratory of the Massachusetts Institute of Technology [255].

In agreement with surveys by the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR, conducted on the frequency of 700 MHz (wavelength 43 cm), the spectrum of the reflected signal consists of two components: a narrow band and a wide band component.

The width of the narrow band component was less than 4 Hz and its intensity was practically unchanged for all of the days of observation. The wide band component occupied a band of frequencies to 400 Hz and changed greatly from day to day. The energy of the reflected radiation in the wide band component was commensurate with that of the narrow band component.

Under the assumption that the wide band component was caused by reflection from the surface of Venus and that the dimension of the reflecting spot, analogous to the Moon, is equal to 1/10 of the visible disk of the planet, the period of rotation of Venus was determined to be greater than 100 days.

If the wide band component of the reflected radiation is a result of reflection from the surface of the planet, then the period of rotation of Venus must consist approximately of 11 days, if its axis of rotation is perpendicular to the direction of the earth observer. However it appears to be more probable that the wide band component is caused not by the rotation of Venus, but has another origin,for example it may represent reflection from areas of moving ionospheric condensation. /87

TABLE III.2.

Base	Hour angle	β	χ	$F_\perp$	$F_\parallel$	$F_\perp - F_\parallel$
800′EW		0,219	0°	0,780±0,009	0,785±0,012	—0,005±0,015
1600′EW	<0	0,438	—64°	0,234±0,015	0,249±0,009	—0,018 0,018
		0,469	—68°	0,220 0,010	0,189 0,009	0,033 0,013
		0,500	—71°	0,192 0,010	0,137 0,010	0,055 0,014
		0,531	—76°	0,151 0,010	0,093 0,008	0,063 0,013
	>0	0,438	—116°	0,341 0,008	0,296 0,010	0,041 0,013
		0,469	—112°	0,280 0,009	0,235 0,011	0,045 0,015
		0,500	—109°	0,219 0,009	0,170 0,011	0,049 0,015
		0,531	—104°	0,157 0,008	0,105 0,012	0,052 0,014
1800′EW	<0	0,500	—70°	0,230 0,008	0,179 0,007	0,052 0,011
		0,562	—75°	0,109 0,009	0,056 0,008	0,053 0,012
		0,625	—81°	0,012 0,008	—0,044 0,007	0,056 0,010
		0,688	—87°	—0,063 0,009	—0,122 0,008	0,060 0,011
	>0	0,500	—110°	0,236 0,008	0,151 0,007	0,085 0,011
		0,562	—105°	0,114 0,009	0,050 0,008	0,064 0,012
		0,625	—99°	0,006 0,008	—0,036 0,007	0,042 0,010
		0,688	—93°	—0,089 0,008	—0,107 0,007	0,018 0,011
2263′NE		0,688	—30°	—0,077 0,007	—0,112 0,013	0,037 0,015
		0,719	—40°	—0,088 0,008	—0,141 0,014	0,052 0,016
		0,750	—53°	—0,100 0,008	—0,153 0,014	0,053 0,016
		0,781	—53°	—0,112 0,007	—0,148 0,011	0,036 0,013
		0,812	—53°	—0,122 0,008	—0,126 0,012	0,004 0,014
1400NS	$-3^h\ 20^m$	0,440	28°	0,340 0,013	0,347 0,015	
	0^h	0,440	0°	0,348 0,009	0,328 0,010	0,012 0,009
	$3^h\ 20^m$	0,440	—28°	0,324 0,011	0,312 0,011	

Tr. Note: Commas indicate decimal points.

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TABLE III.3. SUMMARY OF RADAR MEASUREMENTS OF VENUS

λ	Institution	Period of observation	σ_e	Rotation	Astronomical unit, km	Observers, Bibliographical Reference
3,6cm	Lincoln Lab., Mass. Inst. of Technology, USA	1964 r.	0,009±0,003			D. Karp, W. E. Morrow, W. B. Smith [196]
12,5cm	Jet Propulsion Lab. of Calif., Inst. of Tech., USA	10.III—10.V 1961	0,11±0,02	200—400 days direct	149 598 500 ±500	L. R. Malling, S. W. Golom [224] W. K. Victor, R. Stevens [325] D. O. Muhleman [237]
		1.X—17.XII 1962	0,098± 0,026 0,020	250±40 days retrograde	149 598 757 ±670	R. L. Carpenter [128] R. M. Goldstein [172]
		II—VIII. 1964	0,115 ±0,018	249±6 days retrograde		R. L. Carpenter [129] R. M. Goldstein [173]
23 cm	Lincoln Lab. Mass. Inst. of Tech, USA	21.II—7.X 1964	0,152 ±0,09			J. V. Evans and others [165]
43 cm	Inst. of Radio Tech & Electronics of Academy of Sciences, USSR	18.IV—26.IV 1961	0,08*	>100 days	149 599 300 ±2000	V.A.Kotel'nikov and others [43,44]
		20.X—21.XII 1962	0,157± +0,023 —0,037	250±50 days retrograde	149 597 900 ±500	V.A.Kotel'nikov and others [45]

Tr. Note: Commas indicate decimal points.

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Table III.3. (continued)

λ	Institution	Period of observation	σ_e	Rotation	Astronomical unit, km	Observers, Bibliographical References
		11—30.VI 1964	0,19	230±25 days retrograde	149 598 000 ±400	V.A.Kotel'nikov [47] and others
68 см (440 MHz)	Lincoln Lab., Mass. Inst. of Tech, USA	6.III—18.IV 1961	0,114± +0,062 −0,035	225+275 −110 days direct	149 597 850 ±400	G. Pettengill [255] and others
68,4 см (438 MHz)	USA	21.III—8.IV 1961	0,26		149 596 000 ±200	I. Maron, G. Luchak [225]
70 см	Arecibo Ionospheric Sta., Cornell Univ. USA	15.II—3.XI 1964	$0{,}14^{+0{,}09}_{-0{,}08}$	247±5 days retrograde		R. Dyce, G. Pettengill [158]
73 см	Jodrell Bank, Univ. of Manchester, Eng.	8.IV—25.IV 1961			149 600 000 ±5000	J. H. Thomson [317] and others
		21.XI—20.XII 1962		> 25 days	149 596 600 ±900	J. Ponsonby [269] and others
		5.VI—26.VII 1964		200±100 days retrograde		J. Ponsonby [268] and others
6 м	National Bureau of Standards, USA	28.XI—7.XII 1962	0,2**	230±50 days		W. Klemperer [201] and others
7,85 м	Lincoln Lab., Mass. Inst. of Tech. USA	6.XI—7.XII 1962	0,15** 0,07±			J. James [185] and others

* Refers only to the narrow band component of the reflected signal.
** Average value, great changes occur from day to day.
Tr. Note: Commas indicate decimal points.

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Frequency spectrum surveys in the Jet Propulsion Laboratory and in the Lincoln Laboratory conducted with a higher degree of resolution also revealed that the radiation reflecting spectrum of Venus is very narrow and corresponds to a period of planetary rotation of from 200 to 400 days. The wide band component of the reflected signal was not detected in these measurements.

More complete and accurate data were obtained in measurements near the inferior conjunctions of Venus in 1962 and 1964.

The results of these measurements conducted at the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR are given in Figure III.4 in the form of dependence of the spectrum width of the reflected radiation and visible rotation speed of Venus on the observation data. Calculated values of the dependence for various periods and directions of rotation of Venus are also shown on the same figure.

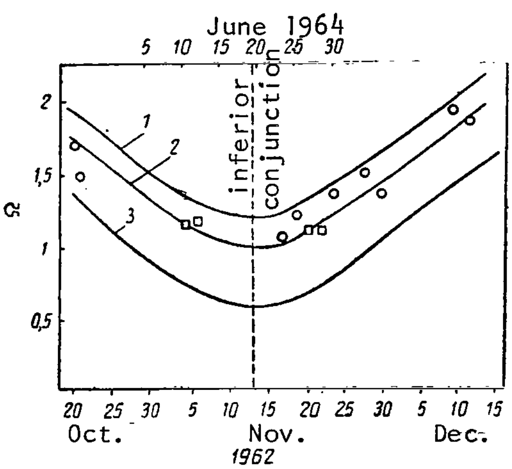

Figure III.4. Angular Speed of the Visible Rotation of Venus Ω, Determined in Accordance with Doppler Broadening of the Reflected Signal Spectrum on the 43 cm Wave. Measurement Results are Shown by Circles for 1962, and by Squares for 1964. Calculated Values of Ω are Indicated by Continous Lines for Retrograde Rotation and for the Following Periods: 1 - 200 days; 2 - 230 days; 3 - 300 days.

The best agreement of calculation to experiment corresponds to retrograde rotation of Venus with a period of 230 ± 25 days. A comparison of the results of measurements in 1962 /88
and 1964 also reveals that the axis of rotation of Venus is close to the perpendicular to the plane of its orbit.

The results of analogous measurements, conducted at the Jet Propulsion Laboratory and at the Arecibo Ionospheric Observatory of Cornell University (USA), are shown in Figures III.5 and III.6. The data obtained also indicate retrograde rotation. The value of the period of rotation of Venus was determined to equal 249 ± 6 and 247 ± 5 days according to measurements at the Jet Propulsion Laboratory and at the Arecibo Observatory, respectively. Accuracy in the determination of the period is actually limited by uncertainty concerning knowledge of the radius of the reflecting surface of Venus.

The long duration of observations of Venus have facilitated the acquisition of more accurate data concerning the orientation of the axis of the rotation of Venus. North Pole coordinates have been determined to equal

$$\alpha = 17^h 04^m \pm 2^h 40^m; \quad \delta = 67° \pm 4°$$

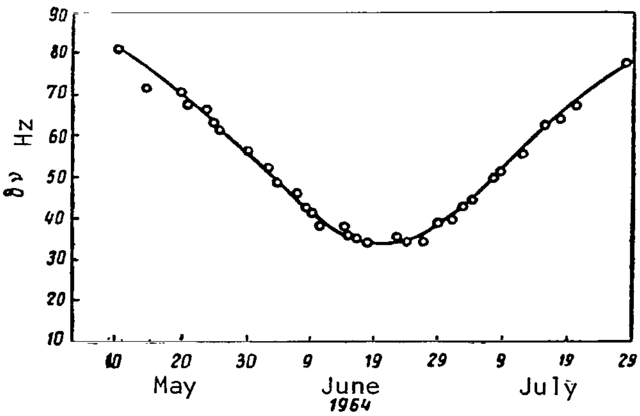

Figure III.5. Maximum (from limb to limb) Doppler Broadening of the Spectrum of Reflected Radiation of Venus on the 12.5 cm Wave as a Function of Measurement Data. The Curved Line Corresponds to Retrograde Rotation with a Period of 249 Days and to Orientation of the North Pole of the Axis of Rotation $\alpha_p = 17^h04^m$; $\delta_p = 67°$.

in the equatorial system of coordinates and $\lambda = 164°$; $\beta = 84°$ in the ecliptic system of coordinates in the Jet Propulsion Laboratory (JPL) experiment and

$$\lambda = 80 \pm 30°; \quad \beta = 86 \pm 2°$$

$$\alpha = 4^h36^m; \quad \delta = 71°$$

in the experiment at the Arecibo Ionospheric Observatory.

Spectral measurements conducted by Ponsonby and others [268] at the University of Manchester (England) and Evans and others [165] at the Lincoln Laboratory of the Massachusetts Institute of Technology were coarser, but did not contradict the data cited above.

The results of the investigations mentioned above concerning the rotation of Venus were obtained from spectroscopic radar measurements of the planet. The existence of some kind of markings on the planetary surface, possessing radiation reflection characteristics different from the average in the radio wave band and obtained through the high degree of resolution achieved in radar measurements of Venus based on selection in time and in frequency, makes it possible to measure the rotation of Venus by using ordinary geometric means in the observation of these markings on the visible planetary disk. The first measurements of this type were made by Goldstein and Carpenter in 1962 [171].

They noted a component corresponding to increased reflection in the reflected signal spectrum. The position of this component changed systema- /90 tically from day to day. The shift of this component on the spectrum relative to the null frequency which corresponds to the central meridian of Venus is shown in Figure III.7. The dates of observations are plotted along the ordinate axis of the graph. The darkened squares correspond to well identified components, and the dashed squares to doubtful ones. The width of the squares characterizes the width of the spectrum of the reflected components.

The relative constancy of this component indicates that it is really caused by some kind of existing formation on the surface of Venus and that its movement is the result of the rotation of Venus.

The relationship between the visible angular speed of rotation of the planet, Ω, and the speed of component shift in the frequency spectrum of the reflected signal, ν, is expressed by the relationship

$$\Omega = \frac{\lambda}{2R} (\sec\varphi \sec\psi)^{1/2},$$

where λ is the wavelength in the experiments conducted, ϕ and ψ are the planetocentric latitude and longitude of the observed formation*.

The longitude of the formation may be calculated by comparison of component shift with the full width of the spectrum. Such a calculation, carried out in accordance with the best spectrums near the inferior conjunction under the assumption that the extreme points of the spectrum correspond to reflection from the limb of the planet, leads to a planetocentric longitude of the formation of $\psi = 23°$. The latitude of the formation was also assumed to equal 23°. Under these assumptions the measured component shift equalled $0.28^{+0.30}_{-0.10}$ Hz/day, which corresponds to a visual angular speed of the rotation of Venus $(2.0^{+0.87}_{-0.41} \times 10^{-7}$ radian $\cdot$ sec^{-1}. When viewed under the assumption that the rotation axis is perpendicular to the plane of the planetary orbit, the data obtained correspond to direct rotation with a period of 1,200 days or to retrograde rotation with a period of 230^{+40}_{-50} days, which corresponds well with the results of spectroscopic measurements.

It must be noted however that due to the rapid decrease and the value of reflection from the initial point of contact toward the limb of the planet, the measured value of the full width of the spectrum of the reflected /91

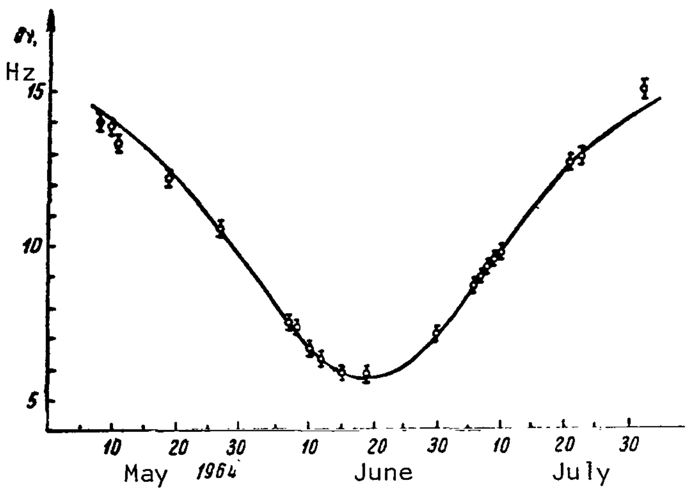

Figure III.6. Maximum (from limb to limb) Doppler Broadening of the Spectrum of Reflected Radiation of Venus on the 70 cm Wave as a Function of Measurement Data. The Curved Line is Obtained as an Approximation of Experimental Data in Accordance with the Method of Least Squares and Corresponds to Retrograde Rotation with a Period of 247 Days and to Orientation of the North Pole of the Axis of Rotation $\lambda_p = 80°$; $\beta_p = 86°$.

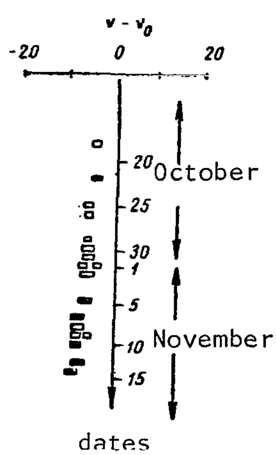

Figure III.7. Frequency Shift of a Spectrum Component Relative to the Central Frequency and Plotted Against the Date.

* The longitude ψ is calculated from the central meridian.

signal may be understated in comparison with the true value. This leads to an overstatement of the longitude of the formation and of the angular speed and to an understatement of the period of rotation. However, within the limits $\phi < 45°$ and $\psi < 45°$, the results of the calculation according to the formula (III.1) depends very little upon ϕ and ψ.

Measurements by Carpenter in 1964 [130] in the reflected signal spectrum revealed two components, one of which, denoted as A, is an area which may correspond to components which were observed in 1962. Such a congruence of 1962 and 1964 components occurs when the period of rotation of Venus is equal to 245 days, giving in this manner still another independent determination of this parameter. Still another independent calculation of the rotation period of Venus was made on the basis of results of radar measurements conducted in Peru [201] on a 6 m wave. During fading conditions of the reflected signal the period of rotation was calculated to take about 180 to 280 earth days.

Recent determinations of the elements of rotation of Venus were conducted by Goldstein [267] through observation of spectrum components of depolarized planetary reflection. The comparison of observations near the inferior conjunctions of the planet in 1964 and 1966 resulted in retrograde rotation with a period of 242.6 ± 0.6 days and coordinates of the North Pole $\alpha = 18^h32^m \pm 20^m$; $\delta = 69 \pm 2°$ in the equatorial system of coordinates and $\lambda = 311°$; $\beta = 86°$ in ecliptical coordinates.

In 1962 the wide band component was again noted in measurements at the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR near the inferior conjunction and was of approximately the same intensity as in 1961. This component was not detected in measurements in the USA.

b) Reflection Function

The investigation of the structure of the surface of Venus from the point of view of the unevenness of its relief is one of the important questions of Venus physics. As shown in § II.3 such data may be obtained on the basis of analysis of the reflection function of radio waves from Venus".

Measurements of the directional characteristics of reflection from Venus were conducted in the USSR and in the USA in a wide band of wavelengths. The function of reflection of Venus, plotted as a result of measurements on the 12.5 cm [129], 23 cm [165], 43 cm [47] and 70 cm [158] waves are shown in Figures III.8, 9, 10 and 11.

The presence in the reflection function of a sharp maximum near $\theta = 0$, corresponding to quasi-specular reflection, is a general result of all measurements. A large part of the energy of the reflected signal is included in the quasi-specular component. /93

It must be kept in mind that a comparative analysis of the reflection function obtained during different measurements (for example, the

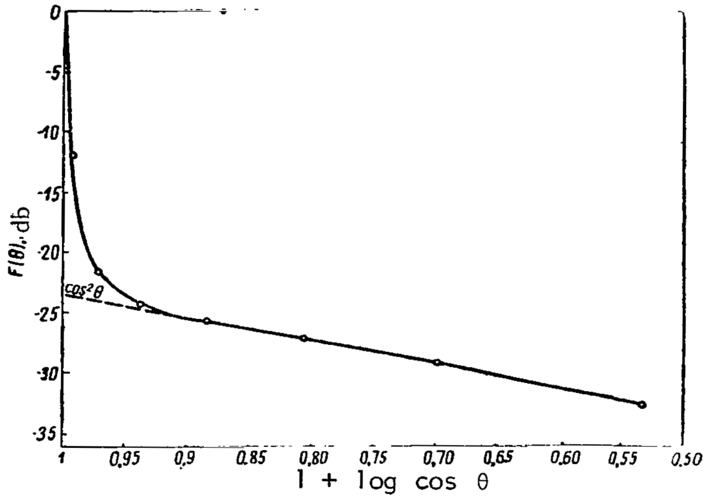

Figure III.8. Characteristic Curve of the Reflection from Venus for the 12.5 Wave .

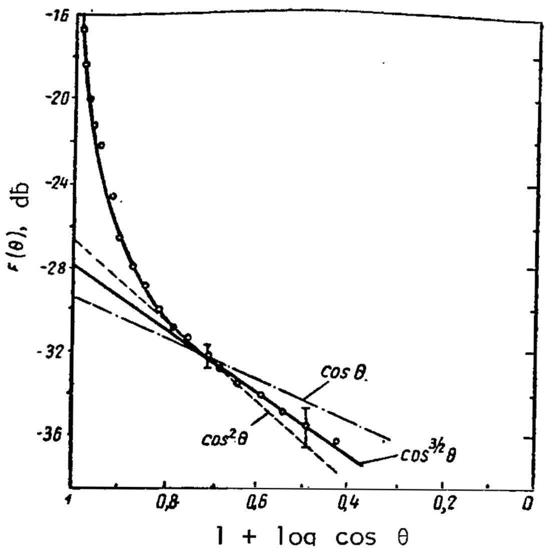

Figure III.9. Characteristic Curve of Reflection from Venus for the 23 cm Wave.

development of its dependence on wavelength) is possible only for measurements conducted with identical resolution. Therefore the functions from Venus cited in Figures III.8 to 11, in particular, may not be directly compared. It is possible, however, to perform an analysis of the dependence on wavelength based on the redistribution of the energy between the quasispecular and the diffused component of reflection.

The reflection function is approximated for the 12.5 cm wave by the analytical function

$$F(\theta) = \frac{208}{209} e^{-16,5 \sin\theta} + \frac{1}{209} \cos^2\theta,$$

analogously applied by Evans and Pettengill for the Moon [164]. Integration of this function with the aid of (II.93) reveals that the diffused component comprises 28% of the full energy of the reflected signal. /94

The diffused component for the 23 cm wave approximates $\cos^{3/2}\theta$; however, of the forms $\cos^2\theta$ and $\cos\theta$ are also not excluded within the accuracy imposed by measurement error variations. The diffused component, determined by integration under a straight line of log $\cos^{3/2}\theta$, comprises 11.2% of the full energy of the reflected signal.

On a 43 cm wave the measured part of the reflection function within the limits $0 < \theta < 50°$ does not support the portion described by the law $\cos^2\theta$. Assuming that when $\theta > 50°$ the reflection is diffused, we find that the diffused component comprises 10% of the full energy of the reflected

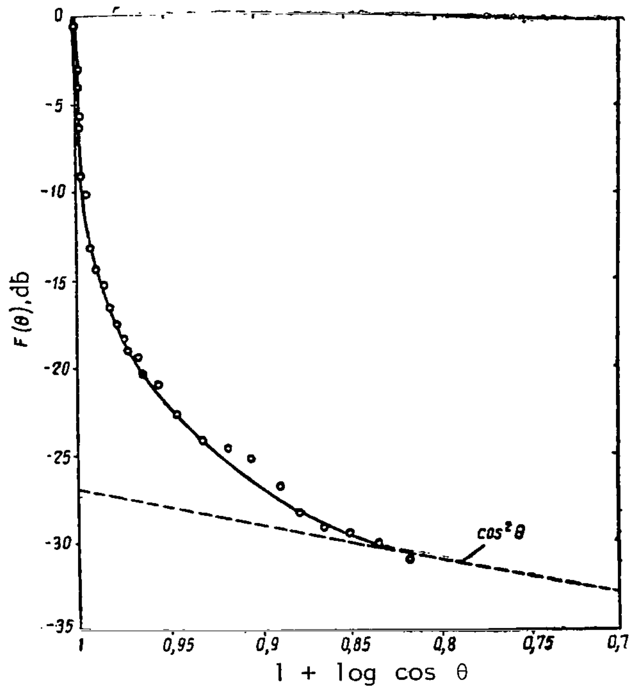

Figure III.10. Characteristic Curve of Reflection from Venus for the 43 cm Wave.

signal. However, in connection with the lack of measurements in this area, the indicated evaluation is considered to be only an upper limit.

On the 70 cm wave the diffused component is 15% of the full energy of the reflected signal.

A comparison of the data cited above indicates an increase in the specific gravity of the diffused component with a decrease in wavelength on waves shorter than 23 cm.

The problem concerning the character of reflection from Venus in the 3 cm wave band is so far not clear. Thus, according to results of measurements in 1964 on the 3.6 cm wave [196], the observers came to the conclusion that the reflected radiation spectrum did not contain a quasispecular component and that all of the reflection was diffused. However, according to measurements in 1966 [288], the reflection function from Venus for the 3.8 cm wave is similar to the reflection function for the 12.5 cm wave (see Figure III.8), though differing from the latter only by a more rapid decrease of reflection at the edge of the planet. As a possible interpretation of this difference Smith [288] pointed out the absorption of radiation at wavelength

c) Effective Cross-Section of Reflection

The results of measurements of the effective cross-section σ_e of radar reflection from Venus are summarized in Table III.3 and are represented on the graph of Figure III.12 in the form σ_e as a function of wavelength λ.

An examination of this graph shows that σ_e apparently does not depend upon wavelength and equals approximately 0.15 in the band of wavelengths from 20 to 70 cm, and significantly decreases on the shorter waves.

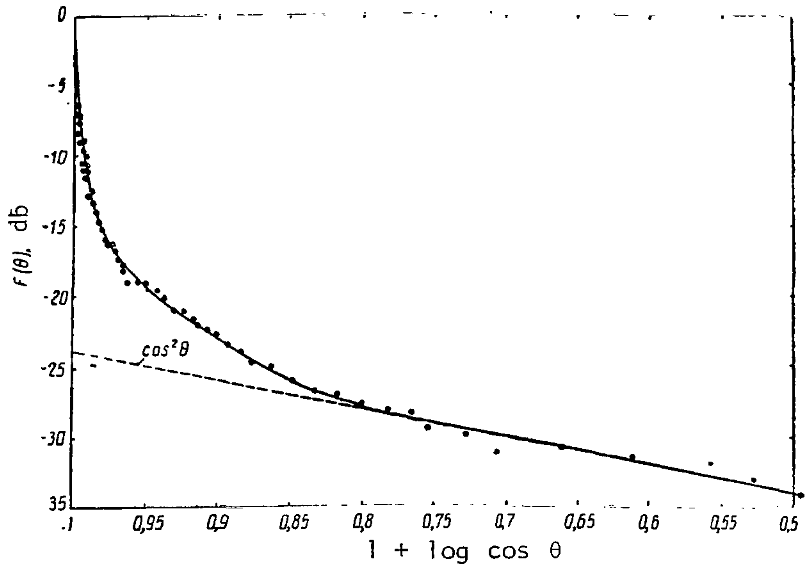

Figure III.11. Characteristic Curve of the Reflection from Venus for the 12.5 cm Wave.

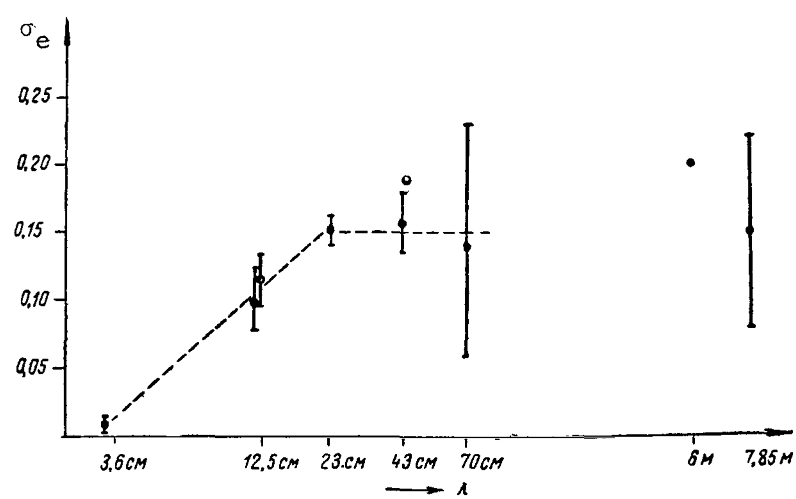

Figure III.12. Effective Cross-Section of Radar Reflection from Venus as a Function of Wavelength.

TABLE III.3

Component	Longitude	Latitude
$A(\alpha)$	0	—33°
$B(\beta)$	—78°	25°
γ	94°	—21°
δ	—69°	26°
ε	—159°	—8°

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The values σ_e entered in Table III.3 and in Figure III.12 are averages for the period of observations. However, the changes reveal that the effective cross-section of the reflection from Venus changes with time. In measurements conducted in 1962, variations in the effective cross-section of the reflection were noted on 12.5 cm [172], 43 cm [45], 6 m [201] and 7.85 m [185] waves. On the 43 cm wave, the value σ_e was changing in various days of observation within the limits 0.12 to 0.18. On the 6m and 7.85 m waves the changes in σ_e were significantly large: on separate days σ_e reached 0.6. In measurements conducted in 1964 on the 70 cm wave, the value σ_e underwent changes from 0.06 to 0.24. In the opinion of the participants in this experiment, this change was definite and was connected with the passage of parts of the planet with diverse reflecting capability through the area surrounding the point of initial contact. A comparison of the results of measurement on various waves reveals that the amount of variations in σ_e apparently depends on the wavelength λ at which the measurements are conducted, increasing with an increase in λ.

Besides the indicated relatively rapid variations in σ_e with a characteristic time of the order of several days, a change in average values may also occur in the effective cross-section of reflection from one inferior conjunction to another. Thus in measurements carried out in 1964 on the 12.5 and 43 cm waves, the average values σ_e for the period of observations increased in comparison with 1962 by approximately 20%. However this rise is on the border of measurement error and demands additional confirmation. According to preliminary results of measurements on the 3.8 cm wave, conducted in 1966 [288, 289], the value σ_e was defined as 0.0125 ± 0.007, which confirms data obtained earlier concerning a sharp decrease in σ_e in the centimeter wave band. Besides this, measurements in 1966 revealed a tendency toward an increase in the effective cross-section of reflection in proportion to an increase in the part of the visible disk of the planet illuminated by the Sun. Smith [288] assumes that such a phase dependence apparently may be interpreted by a change in the atmospheric absorption of Venus during a change in the illumination of the planet by the Sun. In this case one could expect non-symmetry of the spectrum of the reflected signal, caused by a difference in atmospheric absorption on the illuminated and non-illuminated sides of the planet. However, the experiment [288] detected no spectral asymmetry.

d) Depolarization of Reflected Radiation

As is known, when radiation with a circular polarity is reflected from a smooth sphere, the sign of the polarization is reversed. Therefore if a transmitting apparatus emits for example a signal with right circular polari- /97 zation, the receiving antenna must be adapted for the reception of a reflected signal with left circular polarization. However, upon reflection from a rough surface the signal is partially depolarized. This component of the reflected signal, which is a characteristic of a rough reflecting surface, may be measured upon reception by an antenna having the same polarization as the transmitting antenna.

Measurements of the depolarized reflection from Venus were conducted on the 12.5 cm wave [217, 218]. In agreement with the last measurements in 1964 [129], which are apparently highly accurate, the effective cross-section of the radar reflection from Venus in depolarized radiation comprises $\sigma_{ed} = 0.0066 \pm$ $\pm$ 0.005, i.e., 12.4 db less than when measured with matching polarization.

The reflection function of the depolarized component is close to $\cos^2 \theta$.

e) Components of the Spectrum

As has already been mentioned above, in measurements by Goldstein and Carpenter [171] on the 12.5 cm wave components were revealed in the reflected signal spectrum corresponding apparently to local areas in the surface of the planet with an increased reflection capability. An example of a spectrum with such a component is shown in Figure III.13. The location of these particular areas on the planet, determined in accordance with measurements by Goldstein and Carpenter in 1964 [173], is shown in the following Figure III.14.

Measurements conducted in the same year at the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR also revealed a spectrum component indicating an area of increased reflection (Figure III.15). This area coincides with the area B in Figure III.14.

Measurements conducted at the Arecibo Ionospheric Observatory on the 70 cm wave also confirmed the presence of defined areas of increased reflection. The area A, having intersected on July 23, 1964 the central meridian of Venus, is a relatively narrow formation (the width is less than 900 km) extending along the meridian. Area B is more complex and extends further.

/98

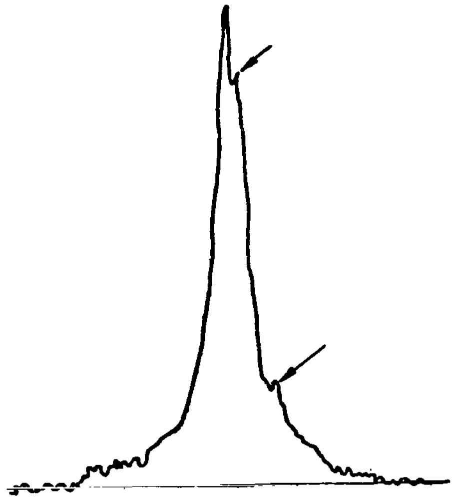

Figure III.13. Frequency Spectrum of Reflection from Venus for the 12.5 cm Wave in May 19, 1964. Areas of Increased Reflection are Marked by Arrows.

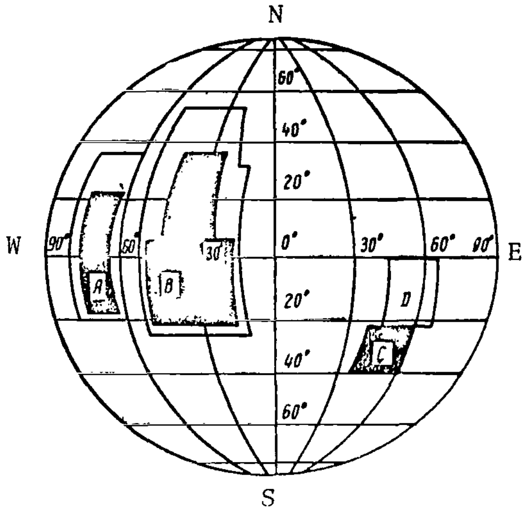

Figure III.14. Chart of the Locations of the Areas of Increased Reflection from Venus according to Measurement Data on the 12.5 cm Wave in 1964.

Nothing is known concerning the nature and the structure of these areas. In this connection it is interesting to note that they also produce depolarized reflection (see Figure III.16).

Measurements of depolarized reflection, carried out by Goldstein in 1966 [267], revealed three additional particular areas. The planetocentric /100 coordinates of the centers of these areas are shown in the table in Figure III.3. The meridian which passes through the center of area A has been taken as the zero meridian. Longitude bearing a positive sign corresponds to the increase in longitude of the point of initial contact during planetary rotation.

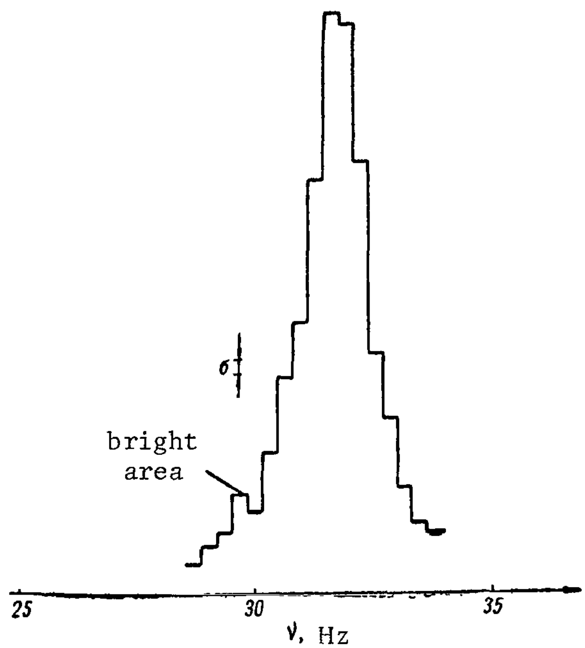

Figure III.15. Frequency Spectrum of Reflection from Venus for the 43 cm Wave, June 12, 1964. The area of Increased Reflection is marked by an Arrow; σ indicates the Root-Mean-Square Error of Measurements.

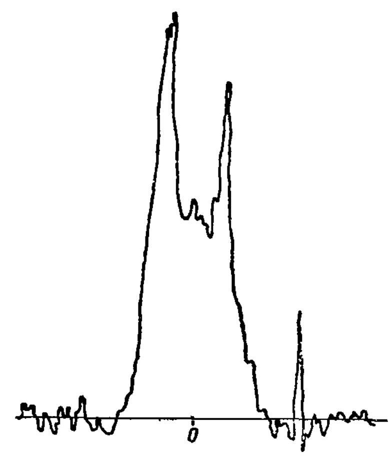

Figure III.16. Frequency Spectrum of the Depolarized Component of Reflected Radiation from Venus for the 12.5 cm Wave, June 25, 1964.

CHAPTER IV

A DISCUSSION OF EXPERIMENTAL DATA PHYSICAL CONDITIONS ON VENUS

1. A Discussion of the Spectrum of Radio Frequency Radiation Models of Venus /101

a) A Model of Venus with a Transparent Atmosphere for Radiowaves.

The existence of a strong dependent of the magnitude of the varying component of planetary brightness temperature, averaged by the disk, on wavelength, (as occurs on the Moon [51] , could be one of the possible reasons for the observed difference in the brightness temperature of Venus in the centimeter and millimeter wave bands. However, such an assumption is not confirmed by direct measurements of the phase dependence of the brightness temperature of Venus according to which the magnitude of the varying component on the 8 mm wave was only about 40°K, at the time that the difference in brightness temperature on the 8 mm and 3 cm waves reached approximately 200°K.

As is known [51], the constant component of the brightness temperature for the Moon, as well as for Venus, decreases with a reduction in wavelength. For the Moon this decrease indicates an increase in the temperature in the depths of the Moon, which is interpreted by Krotikov and Troitskiy [50] as attesting to the presence of heat flux from the interior of the Moon. In principle, a similar mechanism could also take place on Venus as well. However even in a case when the material of the surface of the planet is a dielectric with very low losses, for example quartz, with $\tan \Delta = 2 \cdot 10^{-4}$, for a temperature gradient of grad $T \simeq 20$ deg $\cdot$ m^{-1} is necessary for an interpretation of the fall of brightness temperatures, measured on the 8 mm and 3 cm /102 waves. We are reminded that for the Earth, grad $T = 0.025$ deg $\cdot$ m^{-1}. For the Moon, according to an evaluation by Krotikov and Troitskiy [50], grad $T = 1.6$ deg $\cdot$ m^{-1}. Heat flux density is determined by the well known relationship

$$q = k \cdot \text{grad } T, \qquad \text{(IV.1)}$$

where k is thermal conductivity. For quartz, $k = 0.02$ cal $\cdot$ cm^{-2} sec^{-1} cm $\cdot$ $\cdot$ deg^{-1}. Thus to support the temperature gradient of 20 deg $\cdot$ m^{-1}, a heat flux density $q = 4 \cdot 10^{-3}$ cal $\cdot$ cm^{-2} sec^{-1} is necessary, i.e., 3.5 orders of magnitude greater than the internal heat flux on the Earth. If the heat flux from the interior of Venus is equal to that of Earth, the material of the radiating layer must have a product of the thermal conductivity with the loss tangent equal to

$$k \tan \Delta \simeq 10^{-9},$$

which is one order smaller than the corresponding parameter, even for the surface layers of the Moon consisting apparently of frothy material located essentially in a vacuum. Therefore this possibility for a planet with a heavy atmosphere also seems unlikely.

The investigation cited was carried out under the assumption that the radiating capability of the surface of Venus, determined by the relationship (II.32), does not depend upon wavelength λ. However, in a general case, the dielectric permittivity ε, and therefore radiation capability, are functions of λ. The character of this dependence is determined by the type of polarization. For dielectrics with electron and ion polarization, ε does not depend on wavelength [85]. For dielectrics with orientational polarization, ε increases with an increase in λ near the critical wavelength defined by the relaxation time in this dielectric, and does not depend on λ far from the critical wave. The values of critical waves and of the change in ε are different for various substances. However, ε does not increase with a lengthened wave for a single one of the well known solid or liquid dielectrics. Therefore radiation capability E_v and E_h may only increase with a shortening of the wavelength.

The influence of roughness may also act only in the direction of increasing T_b with a decrease in λ.

Therefore it is not considered possible to explain the experimentally observed decrease in brightness temperatures of Venus in the millimeter wave band by the frequency dependence $E_{(\nu)}$

The mechanism discussed above of frequency dependence of brightness temperature of Venus pertained to a case when all of the radiation of the planet was assumed to be caused only by the surface. However the dense atmosphere of Venus may be absorbent, and therefore also radiating within the radio wave band. /103

Atmospheric absorption occurs in a general case through molecular absorption by component gases of the atmosphere, through absorption by aerosol particles and through absorption by charged particles located in the ionospheric layers of the atmosphere. All of the indicated types of absorption are considered selective. This selectivity opens new possibilities for the construction of models of Venus, complying with the experimental spectrum of brightness temperature.

Models of Venus with selective absorption of radio waves in its atmosphere reduce, in fact, to two groups.

In the first group of models, later called models with a "cold atmosphere", it is assumed that the atmosphere of Venus is colder than the surface and that the atmosphere is absorbent in the millimeter band and transparent on longer waves (see Figure IV.1).

In this case planetary radiation in the centimeter band is emitted from

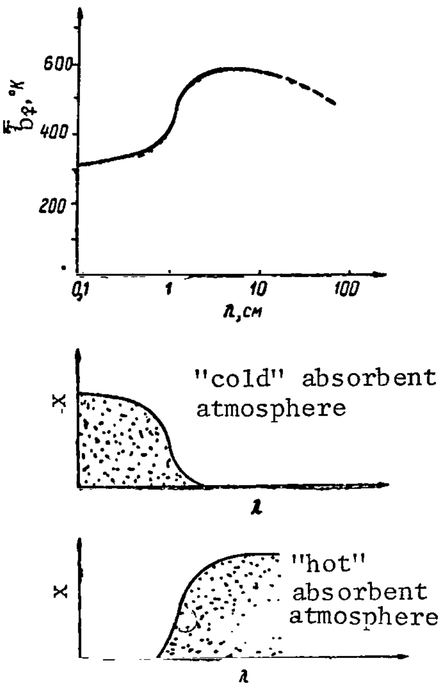

Figure IV.1. Schematic Representation of Absorption as a Function of Wavelength in Models of Venus with "cold" and "hot" Absorbent Atmospheres.

the "hot" planetary surface. An actual decrease in brightness temperature on the shorter waves is caused by absorption and re-emission by the colder atmosphere.

In the second group of models, called models with a "hot atmosphere", it is assumed that the atmosphere of Venus contains a certain electrically active medium, which is considered to be the source of high temperature radiation in the centimeter and decimeter wavelength bands. In the millimeter /104
band this medium is assumed to be transparent (Figure IV.1) and observed radiation is caused by the planetary surface, which has a relatively lower temperature.

We will examine in detail the indicated groups of Venus models.

b) A Model of Venus with a "Cold" Atmosphere

The model of Venus with a "cold" atmosphere was suggested in 1959 by Kuz'min and Salomonovich [52] for the interpretation of a measured (by the authors) reduction in brightness temperature of Venus in the millimeter band in comparison with brightness temperature on centimeter waves (Figure IV.2). In recent years a series of attempts to interprete the results of changes with the aid of a model of Venus with a "cold" atmosphere consisting of various components, present or anticipated in the atmosphere of Venus and considered to be absorbent in the millimeter wave band, have been undertaken.

In connection with the fact that the first, and so far the single, reliably established component in the atmosphere of Venus is carbon dioxide, the first quantitative investigation of the model of Venus with a "cold" atmosphere, conducted by Barrett [106], pertained to carbon dioxide.

Under normal pressure CO_2 is a symmetrical molecule, incapable of reaction with ultrahigh frequency radiation and therefore not inducing absorption. However, at elevated pressures generated during molecular collisions, deformations create for a short time an induced dipole moment, /105
which generates non-resonant absorption of ultrahigh frequencies. The coefficient of absorption depends upon pressure p and on frequency ν and is determined by the relationship

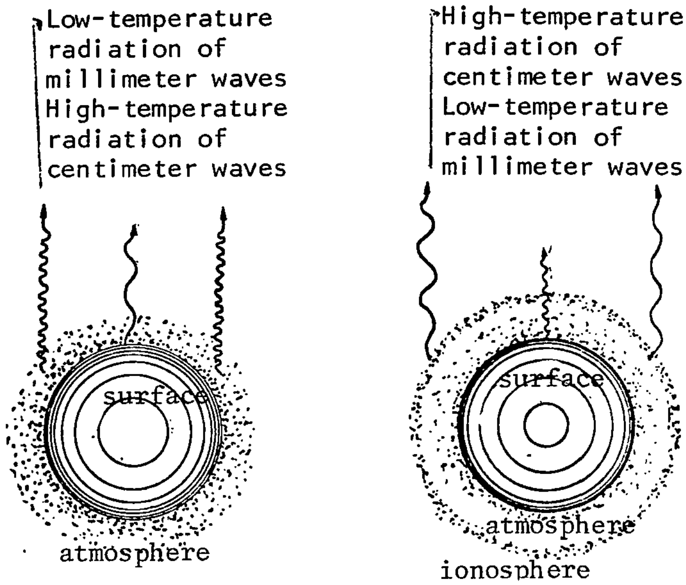

Figure IV.2. Models of Venus with "Cold" and "Hot" Atmospheres.

$$\varkappa = \varkappa_0 \frac{p^2 \nu^2}{T^m}. \qquad \text{(II.27)}$$

A calculation made by Barrett for the Venus atmosphere, consisting of 75% CO_2 and 25% N_2, revealed that with a pressure near the surface of 30 atm, satisfactory agreement occurs with data known to the author at the time, with observations on the 8 mm, 3 and 10 cm waves.

The calculated pressure on the surface of the cloud layer for CO_2 - N_2 in the atmosphere was determined by Barrett to equal 1.1 atm, which is significantly lower than the quantity 90 mb obtained by Dol'fyus in observations of the screening of Regulus [27]. This served as a basis for criticism of this calculation by Sagan [282]. Besides this, Sagan refuted Barrett's acceptance, for the non-illuminated side of Venus, of the adiabatic temperature gradient in the atmosphere under the clouds on the basis of available data concerning significant phase variations in brightness temperature. This indicated, in Sagan's opinion, a significantly higher temperature on the illuminated side of the planet. This was interpreted by Sagan as an indication that the temperature gradient on the non-illuminated side of the planet is significantly less than the adiabatic temperature. In Sagan's opinion, absorption in CO_2 clearly cannot explain current experimental data.

Sagan's statement concerning the significant difference between the temperature of the illuminated and non-illuminated side of Venus was based on insufficiently accurate results of phase dependence measurements $\bar{T}_{b♀}(\Phi)$, conducted by Mayer and others [288] and on an erroneous reference to Lilley's observations [219] in which the phase variation T_b♀ was not even investigated. Subsequent measurements by Mayer and others [230] revealed that the difference in brightness temperatures between the illuminated and non-illuminated sides of Venus was significantly less than Sagan had accepted. Moreover the content of CO_2 in the atmosphere of Venus in accordance with subsequent measurement data in the infrared range (see § 1.3) also proved to be essentially lower than Barrett and Sagan had accepted. In this connection Salomonovich [84], in a spectrum analysis for Venus's atmosphere, obtained 20% CO_2 and 80% N_2 with a pressure at the level of the cloud layer of 90 mb. Accepting for

simplification that $\gamma = C_p/C_v$ is a constant at all altitudes up to the cloud layer, he also came to the conclusion that the observed decrease in brightness temperature on waves shorter than 3 cm could not be explained by absorption /106
by carbon dioxide in the atmosphere of Venus alone. Thaddeus in [316], reexamining Barrett's calculations, having accepted the atmospheric composition 10% CO_2 and 90% N_2, obtained satisfactory agreement of the calculation with experimental data (without the measurements of Kislyakov and others [35] on the 4 mm wave, and not accounted for by them) at a pressure at the surface of the planet of 100 atm. Finally Barrett, together with Staelin [109], repeated his calculation for the atmosphere, also containing 10% CO_2 and 90% N_2, for various values of the temperature gradient β. The data obtained by them revealed that when $\beta = 4.86$ deg $\cdot$ km^{-1} a pressure of more than 300 atm would be required in order to approximate the experimental data. However even in this case the calculated spectrum in the intermediate range 0.8 - 3 cm had insufficient steepness for agreement with experimental data. The change with reference to the content of CO_2 and N_2 did not substantially influence the results. The steepness of the calculated spectrum in the intermediate area may be increased by an increase in the temperature gradient. However, even when $\beta = 7$ deg $\cdot$ km^{-1}, a pressure of approximately 200 atm is required. A further increase in β increases the steepness of the spectrum even further, but does not decrease the pressure. However in all investigations in the 4 mm wavelength band, agreement between calculation and experiment still remains poor.

Thus carbon dioxide in the atmosphere of Venus shows satisfactory concurrence of calculation, using the model with the "cold" atmosphere, with experiment in the wavelength band longer than 4 mm; however the pressure demanded in this connection at the surface of the planet must reach 200 - 300 atm.

In connection with the series of reports concerning the detection within the atmosphere of Venus of water vapor [116, 150, 312] possessing strong resonant lines of absorption on the waves $\lambda = 1.62$ mm and $\lambda = 1.35$ cm, and caused by the interaction of ultrahigh frequency radiation fields with the dipole electric moment of a molecule of H_2O, numerous attempts were made to calculate this absorption for the interpretation of the Venus model with a "cold" atmosphere. In this connection it was also expected that the additional absorption in water vapor would decrease the amount of absorption in CO_2 and for this reason decrease the required pressure in the planetary atmsophere.

The first attempt, undertaken by Barrett [106], revealed that an addition to the atmospheric composition of Venus of 1 - 3% of water vapor decreases the pressure, required for the satisfaction of experimental data, from 30 atm to 20 - 10 atm. However such a high water vapor content contradicts even the most optimistic results of Strong's first measurements [312]. Moreover in this case there must be in the calculated spectrum of radio frequency radiation of Venus a deep gap on the 1.35 cm-wave water vapor absorption. /107
This is not supported by the results of direct measurements in this wave band,

conducted by Welch and Thornton [329] and Drake [155], although analogous measurements by Barrett [110] apparently indicate the presence of such a gap.

Thus an attempt to interpret the Venus model with a "cold" atmosphere by water vapor absorption in the planetary atmosphere has thus far been unsuccessful.

Numerous attempts have also been made to explain the Venus model with a "cold" atmosphere by absorption in the cloud layer consisting of drops of water.

The first attempt undertaken by Sagan [283] revealed that through appropriate matching of water content with cloud layer depth, it is possible to obtain satisfactory agreement of calculated values with experimental data published before 1960.

A calculation made by Salomonovich [84], including Venus measurement data on the 4 mm wave [35], revealed that the correspondence between the calculated spectrum, dependent on absorption in aqueous clouds, and experiment is not completely satisfactory. Especially poor agreement is obtained in the millimeter band where the calculated spectrum, while satisfying measurements on the 8 mm wave, does not satisfy measurements on the 4 mm wave, and vice versa

Deirmendjian [143] made an approximate calculation (without solving the transport equation and without calculating the characteristic radiation of the planetary atmosphere) for the case of clouds and rain similar to those of Earth, which included distribution statistics of water drop dimensions and the calculation of both absorption and diffusion within them. He obtained an analogous result: the calculated spectrum satisfied measurement data on the 10 and 3 cm and 8 mm wave, but differed from measurement results on the 4 mm wave.

Barrett and Staelin [109] examined a cloud of water drops in equilibrium with the water vapor under it. The depth and density of the cloud was taken as 6 km and 1 g $\cdot$ m^{-3}. The water vapor pressure at the base of the cloud was 25 mb. The temperatures at the top and at the base of the cloud were 270 and 300°K, respectively. The calculation, made for pressures of 2.20 and 100 atm, revealed that basically the absorption was induced not by the cloud but by the water vapor under it. It was in this connection that the water vapor considerations mentioned above came into force.

All of the above mentioned investigations of the Venus model with a "cold" atmosphere had the problem of the analysis of how one or another component, present or assumed in the Venus atmosphere and possessing selective absorption in the radio wave band, might explain known data concerning the brightness temperature spectrum of Venus.

Kuz'min [57, 63] examined the more general problem of the determination of the electrical characteristics of the absorbent layer in a general form in accordance with the known radio frequency radiation spectrum of Venus. The /108 examination was conducted on the basis of the general theory of radio frequency radiation from a planet with an absorbent atmosphere, developed in § III.2.

We shall determine what the dependence of absorption in the planetary atmosphere on wavelength must be in order to satisfy the measured spectrum of brightness temperature on Venus. (Figure III.1).

For these calculations we shall evaluate the required surface temperature in accordance with the brightness temperature measured in the 10 cm wavelength band, where the planetary atmosphere in the model with a "cold" atmosphere is transparent. Accepting, in accordance with radar measurements, that for the model with a "cold" atmosphere the dielectric permittivity of the surface material ε = 3-4, which corresponds to I_1 (0, ε) = 0.86 and $\overline{T}_{b♀} \cong 580°K$, we obtain $T_{e0} \cong 680°K$. We shall accept the temperature of the cloud layer, in agreement with infrared measurement data as approximately 250°K. We will place the temperature gradient in the layer under the clouds equal to the adiabatic:

$$\beta_a = \frac{Ag}{C_p}, \tag{IV.4}$$

where $A = 2.39 \cdot 10^{-8}$ cal/erg - the thermal equivalent of work, g is the acceleration of gravity, equal to 835 cm $\cdot$ sec^{-2} for Venus, C_p is thermal capacity at a constant pressure. However, the chemical composition of the atmosphere and therefore the value C_p for Venus is unknown. Spectroscopic investigations have revealed that apparently the basic part of the planetary atmosphere is composed of gases, which cannot be detected spectroscopically. Such components may consist of nitrogen or inert gases. For nitrogen C_p = = 0.25 cal $\cdot$ g^{-1} deg^{-1} and β_a = 8 deg $\cdot$ km^{-1}. For argon C_p = 0.125 and β_a = = 16 deg $\cdot$ km^{-1}. For further calculations we shall assume a nitrogen atmosphere and β_a = 8 deg $\cdot$ km^{-1}.

The functions $\overline{T}_{b♀}$ [τ (λ)], as shown on the graph in Figure IV.3 were calculated for the parameters chosen above for the Venus model with a "cold" atmosphere, ε = 3, T_{e0} = 680°K, T_{c1} = 250°K, β = 8 deg $\cdot$ km^{-1}; for various conditions of absorption distribution by altitude. The continuous curves refer to absorption by the entire depth of the atmosphere with an exponential distribution by altitude. The dashed line corresponds to a layer with equal absorption by altitude, included between altitudes having temperatures of T_1 = 300°K and T_2 = 250°K. The functions $\overline{T}_{b♀}$ [τ (λ)] for a parabolic layer /109
with Δh_0 = 5 km for T_m = 300 and 400°K are plotted with dot-and-dash lines.

An examination of the cited relationships reveals that in order to satisfy a Venus brightness temperature of $\overline{T}_{b♀}$ = 350 - 400°K, measured in the millimeter wave band by absorption in the entire thickness of the atmosphere, the required atmospheric thickness on these waves, also depending on H, must be very great. Thus, for example, when H = 7 km, obtained through observations of the screening of Regulus, the satisfaction of radio observation data demands the high and therefore unlikely value $\tau_{\lambda 4\text{-}8\ \mathrm{mm}} \cong 100$.

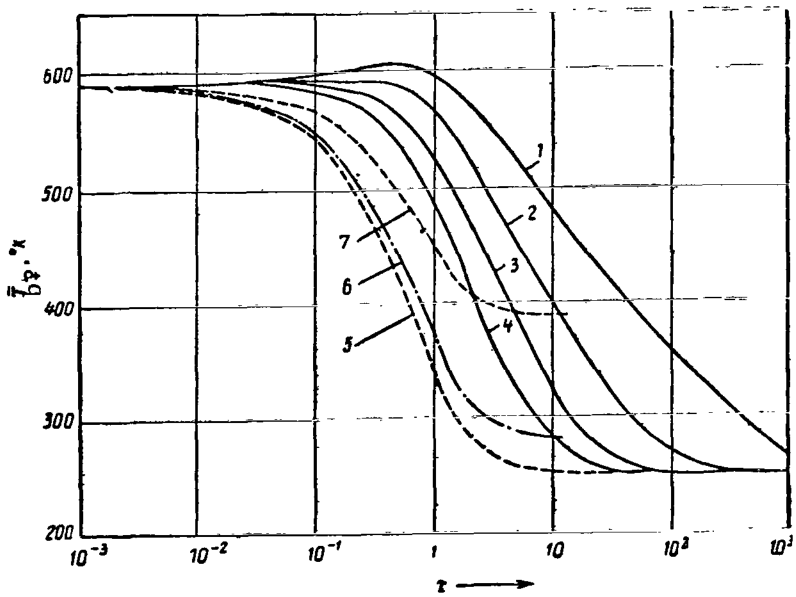

Figure IV.3. Brightness Temperature of Venus, Averaged by the disk, as a Function of Optical Depth of the Absorbent Atmosphere for $\varepsilon = 3$, $T_{e0} = 680°K$, $T_{c1} = 250°K$, $\beta = 8$ deg · km^{-1} for the Following Cases: 1, 2, 3 and 4) the whole mass of the atmosphere is absorbent, H = 7 km, 10.5 km, 15 km and 21 km, respectively; 5) a homogeneous layer is absorbent, enclosed between layers with temperatures T_1 = 300 °K and T_2 = 250°K; 6,7) a parabolic absorbent layer with $\beta\Delta h_0 = -40°K$ and T_m = 300 and 400°k, respectively.

As is known [94], the altitude of a uniform atmosphere depends on temperature

$$H = \frac{R}{\mu}\frac{T}{g}. \qquad \text{(IV.5)}$$

Here R is a universal gas constant, and μ is molecular weight. Then accepting, /110
as earlier, that H = 7 km in the layer under the clouds, we obtain H ≅ 20 km

for the lower layers of the atmosphere. However, even in this case an optical thickness of the absorbing layer in the millimeter band $\tau \cong 3$ is required.

It is apparent from this same figure (IV.3) that brightness temperatures 350 - 400°K may be obtained with significantly less optical thickness if the absorption occurs in a layer of finite thickness situated close to the upper edge of the cloud layer. In fact, a layer with T_m = 300°K and Δh_0 = 5 km must have $\tau_{\lambda 4-8 \text{ mm}}$ of a value of approximately 1.

On the basis of what has already been written, it seems more probable that the absorbent medium responsible for the decrease in brightness temperature of Venus in the millimeter wave band is included in the layer of finite thickness located close to the upper edge of the cloud layer, and not distributed throughout the entire thickness of the planetary atmosphere.

For a uniform layer with T_1 = 300°K and T_2 = 250°K, Figure IV.4 shows optical thickness τ, and therefore absorption κ, as functions of wavelength, required to obtain the measured spectrum $T_b^{♀}(\lambda)$ (Figure III.1).

As is known, nephelometric [95, 96] and polarization [223] measurements of Venus in the optical band indicate a high content of aerosol in its atmosphere. It is possible that the cloud layer of Venus is also aerosol. Under Earth conditions, atmospheric aerosol (clouds, fog) is absorbent for radio frequency radiation in the shortwave portion of the centimeter and millimeter wave bands (see for example, [3]). In this connection Kuz'min [57] examined in a general form the possibility of explaining the radio frequency radiation spectrum of Venus through selective absorption by aerosol particles.

Weakening of electromagnetic radiation by aerosol particles, small in comparison with wavelength, is determined by the relationship [3]

$$\varkappa(\lambda) = 56{,}5\,\frac{C_1(\lambda)\,M}{\lambda}, \quad [\text{см}^{-1}]$$
$$C_1(\lambda) = \frac{\varepsilon''(\lambda)}{[\varepsilon'(\lambda)+2]^2+\varepsilon''(\lambda)^2}, \qquad \text{(IV.6)}$$

where M is the mass of the absorbent particles, and ε' and ε'' are the real and imaginary parts of the complex dielectric permittivity of the particle material.

The optical thickness of a uniform layer with thickness Δh is

$$\tau(\lambda) = \varkappa(\lambda)\ \Delta h. \qquad \text{(IV.7)}$$

It is not difficult to show that in order to obtain the spectral function of absorption, represented in Figure IV.4 by the quantities ε' and ε'', the /111

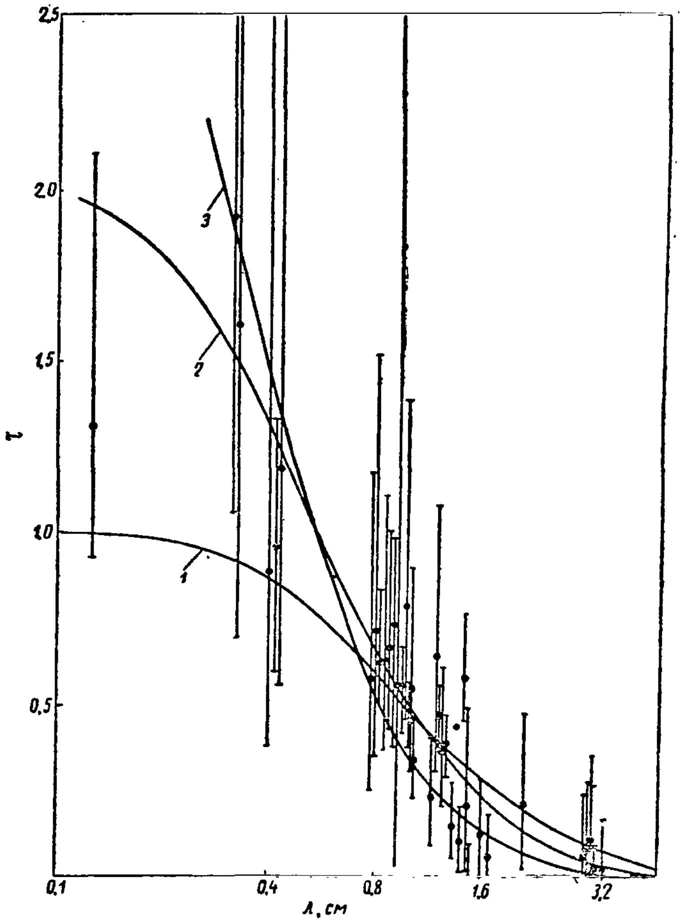

Figure IV.4. Optical Thickness of an Atmosphere with a Uniform Absorbent Layer (T_1 = 300°K, T_2 = 250°K) as a Function of Wavelength, required to Obtain Measured Spectrum $T_{b♀}(\lambda)$ (Figure III.1).

aerosol materials must change sharply with changes in λ in the shortwave portion of the centimeter wave band.

In agreement with [49], ε' and ε'' of rock, volcanic rock and volcanic ash in the band which interests us do not depend upon wavelength. Therefore it is not considered possible to explain the observed spectrum of radio frequency radiation of Venus by selective absorption in dust aerosol composed of the matter mentioned. /112

The required characteristics are possessed by low-viscosity polar liquids, whose frequency functions ε' and ε'' are described by the relationships [85].

$$\varepsilon'(\lambda) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + y^2}$$
$$\varepsilon''(\lambda) = \frac{(\varepsilon_0 - \varepsilon_\infty) y}{1 + y^2}, \qquad \text{(IV.8)}$$

where

$$y = \omega t_p \frac{\varepsilon_0 + 2}{\varepsilon_\infty + 2},$$

t_p is the relaxation time of the polar molecules, ε_0 and ε_∞ are the dielectric permittivity of the substance on frequencies

$$\omega_0 \ll \frac{1}{t_p} \text{ and } \omega_\infty \gg \frac{1}{t_p}.$$

Substituting (IV.8) and (IV.7), we obtain the calculated function $\kappa(\omega t_p)$ and, therefore, $\tau(\omega t_p)$. The results of the calculation are shown graphically in Figure (IV.5) and reveal that the form of the curve $\kappa(\omega t_p)$ is noncritical /113 with respect to the parameters ε_0 and ε_∞. The location of the knee corresponds

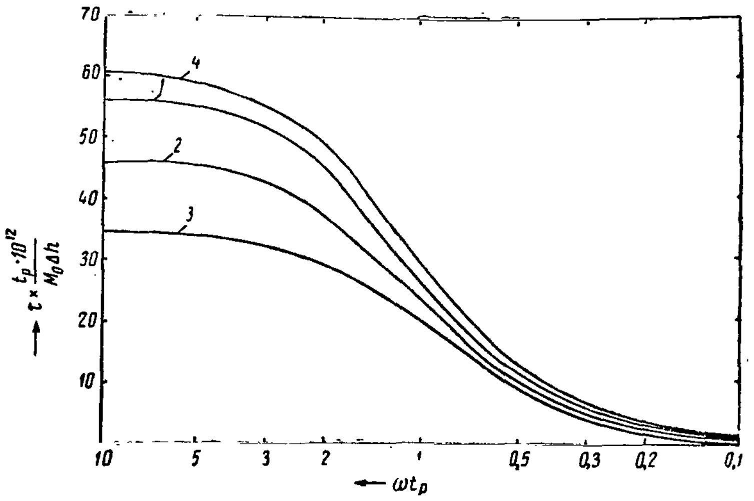

Figure IV.5. Computed Optical Thickness τ of the Polar Liquid Aerosol as a Function of Frequency ω and Relaxation Time t_p for: 1) $\varepsilon_0 = 81$, $\varepsilon_\infty = 3$; 2) $\varepsilon_0 = 20°$; $\varepsilon_\infty = 3$; 3) $\varepsilon_0 = 10$, $\varepsilon_\infty = 3$; 4) $\varepsilon_0 = 20$, $\varepsilon_\infty = 2$.

to frequencies $\omega \cong \frac{1}{t_p}$.

The quantity

$$\tau(\omega t_p)\, x\, \frac{t_p \cdot 10^{12}}{M_0 \Delta h}.$$

is placed along the ordinate axis.

Figure IV.4 shows a comparison between experimental data and calculated data for various parameters t_p and $\tau(0) = \tau_{\lambda \to 0}(\omega t_p)$. Satisfactory agreement between experiment and calculation occurs when $t_p = (1.5\text{-}5) \cdot 10^{-12}$ sec. and $\tau(0) = 1\text{-}4$.

We shall evaluate the required quantity of the absorbent substance. Transforming (IV.6) for $\lambda \to 0$, we obtain:

$$\tau(0) = \frac{3 \cdot 10^{-10} M_0 \Delta h}{t_p} \frac{\varepsilon_0 - \varepsilon_\infty}{(\varepsilon_0 + 2)(\varepsilon_\infty + 2)},$$

from which

$$M_0 \Delta h = \frac{\tau(0)\, t_p}{3 \cdot 10^{-10}} \frac{(\varepsilon_0 + 2)(\varepsilon_\infty + 2)}{\varepsilon_0 - \varepsilon_\infty}. \tag{IV.9}$$

Here M_0 is the quantity of the absorbent substance in 1 cm^3 of the atmosphere of Venus. Assuming, in agreement with the above $\tau(0) = 1\text{-}4$ and $t_p = (1.5\text{-}5) \cdot 10^{-12}$ sec and setting different values ε_0 from 81 to 10 and $\varepsilon_\infty = 3\text{-}2$, we obtain $M_0 \Delta h = 0.1 - 0.2$ g of the absorbent substance in a column of the layer with a cross-section of 1 cm^2. With the thickness of the absorbent layer

$$\Delta h = \frac{T_1 - T_2}{\beta} \cong 6 \text{ km}$$

this corresponds to the required absorbent substance concentration in the cloud layer of Venus $M_0 = 0.2 - 0.4$ g $\cdot$ m^{-3}, i.e., it is even lower than the average water content of earth clouds [94].

The calculated radio frequency radiation spectrum of Venus is shown in Figure IV.6 and within the accuracy of measurement error it corresponds with measured results. The atmosphere contains the specified quantity of liquid mentioned above, in the form of an aerosol. Thus it is possible to explain the decrease in the brightness temperature of brightness temperature of radiation from Venus in the millimeter portion of the spectrum by citing absorption in the watery atmospheric aerosol, at a temperature of 250-300°K and containing 0.1-0.2 g · cm^{-2} polar liquid with a relaxation time t_p = = (1.5-5) · 10^{-12} sec.

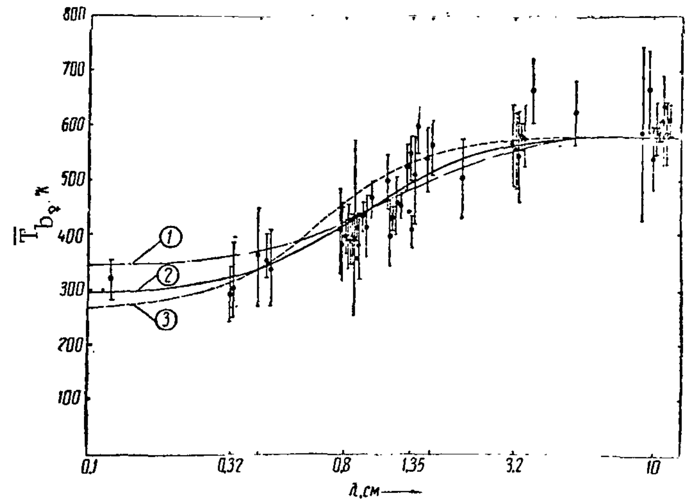

Figure IV.6. Calculated Spectrum of the Radio Frequency Radiation of the Model of Venus with a "cold" Atmosphere consisting of an Absorbent Aerosol of Polar Fluid with Relaxation Times 1) t_p = = $5.3 \cdot 10^{-12}$ sec; 2) $t_p = 3 \cdot 10^{-12}$ sec; 3) $t_p = 1.6 \cdot 10^{-12}$ sec.

Several functional derivatives of methane, ethane and benzene, for example, CH_3OH, $(C_2H_5)_2O$, C_6H_5Cl, C_6H_5Br and others have relaxation times close to the required amount. However, according to Mueller [235], the presence of hydrocarbons in the atmosphere of Venus in significant amounts is unlikely.

Water is also a polar fluid; however at temperatures above the freezing point its relaxation time is substantially lower than the required amount (at temperature T = 288°K, t_p = 0.5 · 10^{-12} sec). Therefore absorption in an aerosol consisting of drops of water with T > 273°K corresponds poorly with experimental data. However, water drops in earth clouds are frequently found in a super-cool condition [94]. Basharinov and Kutuza [10] pointed out that ultra-cool drops of water may also explain the experimental data in connection with an increased relaxation time with a decrease in temperature (for water with t = -10°C, they obtained through extrapolation t_p = 2.5 · 10^{-12} sec). /114

Barrett and Staelin [109], having investigated a series of individual cases, reached analogous conclusions. According to their calculations, the closest agreement with experiment takes place for a cloud layer which is absorbent in proportion to the square of the frequency. This corresponds to the aerosol, which we examined above, consisting of a polar liquid with a critical wavelength situated in the intermediate portion of the spectrum of Venus.

According to Barrett and Staelin, a stable aerosol with particle dimensions significantly shorter than wavelength does not provide the required spectrum form and moreover requires a dust concentration near the planetary surface of about 100 g $\cdot$ m^{-3}, which is approximately 4 orders of magnitude greater than that occuring on earth during dust storms. /115

An increase in particle dimensions so that diffusion, as well as absorption, may play a role, improves the situation somewhat. With particle dimensions 0.3 - 0.6 mm and density 10 g $\cdot$ m^{-3}, the calculated brightness temperature spectrum becomes noticeably steep between λ = I cm and λ = 2. However, in this case poor concurrence with the results of measurements in the millimeter band occurs. In principle it is possible to attempt to diminish this discrepancy by the addition of another mechanism of absorption. However, the addition of a carbon-nitrogen atmosphere with a surface pressure of 20 atm does not provide the required concurrence.

To summarize the foregoing, it may be concluded that the measured brightness temperature spectrum of radio frequency radiation of Venus may be interpreted within the framework of a model with a "cold" atmosphere which is absorbent in the millimeter wavelength band. The problem of the nature of the absorbent agent cannot be unequivocally resolved. To be specific, it may be aerosol consisting of 0.1 - 0.2 g $\cdot$ cm^{-2} polar fluid with relaxation time (1.5 - 5) $\cdot$ 10^{-12} sec.

c) The Model of Venus with a "Hot" Atmosphere

In the models with a "hot" atmosphere, it is assumed that the atmosphere of Venus possesses a certain electrically active medium, which serves as a source of supplementary high temperature radiation in the centimeter and decimeter wavelength bands. In the millimeter band this medium is assumed to be transparent, and the observed radio frequency radiation is caused by the planetary surface, which is considered to be relatively colder.

The first model of Venus with a "hot" atmosphere was suggested by Jones [189]. As the electrically active medium, he suggested the ionosphere with an electron temperature of 600°K and considered to be optically thin in the millimeter band and optically thick on longer waves. He calculated that such a model satisfactorily concurs with experimental data if the integral of the square of the electron density satisfies

$$\int N^2 dz \cong 10^{25}\,\mathrm{cm}^{-5}.$$

An ionospheric thickness z = 100 km demands an electron concentration $N \simeq 10^9$ cm^{-3}. It is known [3] that in the Earth's ionosphere the maximum electron density is approximately 10^6 cm^{-3}. Danilov [21] demonstrated that the ionospheric electron concentration of Venus must be of the same order if /116 its atmosphere consists mainly of CO_2 and if the ionizing source is solar ultraviolet radiation. Jones' model demands an electron concentration approximately 3 orders of magnitude greater.

As a possible mechanism of high ionization, Jones suggested solar corpuscular radiation which, in view of the weak magnetic field of Venus (less than 1/30 of the earth), may penetrate the atmosphere of Venus. He also pointed out that in this case the anticipated electron density dependence on solar radiation may be the reason for brightness temperature dependence on the phase of planetary illumination by the Sun.

Such a mechanism for the creation and support of an electron density in the ionosphere of Venus, surpassing the maximum earth level by a factor of 3 orders of magnitude, was subject to criticism by Kellog and Sagan [33]. They showed that the ionization mechanism of the solar wind may be only about 30 times more effective than solar ultraviolet ionization, whereas an increase in N of 3 orders of magnitude requires an increase in the ionization factor of 6 orders of magnitude. Moreover, the radio astronomic observation data utilized in the construction of this model refers to the side of Venus not illuminated by the Sun, where solar ionizing activity is even less.

As is known, the ionospheric electron density is determined by the relationship of the ionizing agent and the coefficient of recombination. Danilov and Yatsenko [22] examined the possibility of obtaining high electron concentrations in the night ionosphere of Venus through a decrease in the coefficient of electron recombination. Such a situation might arise if, beginning with certain altitudes, the atmosphere of Venus broke up and became fully elemental. The atomic recombination coefficient is $\alpha \cong 10^{-12}$ cm^3 sec^{-1}. A second possibility consists of the fact that the assumption in [21] of the transformation reaction of elemental ions O^+ into molecular ions through a charged transfer with CO_2 molecules, may not occur as effectively as accepted in [21] in the analogy to the earth's ionosphere. Then the ions O^+ would disappear also in a radiation recombination reaction with $\alpha \cong 10^{-12}$ cm^3 sec^{-1}. With Jones' evaluation of $N^2dz = 10^{25}$ cm^{-5}, $\alpha = 10^{-12}$ cm^3 sec^{-1} corresponds to an aggregate quantity of recombinations in a column of the atmosphere of Venus of approximately 10^{13} recombinations $\cdot$ cm^{-2} sec^{-1}. In this case, the question of the possibility of supporting a high electron concentration in the ionosphere of Venus leads to an examination of the possibility of the /117
existence in the night ionosphere of Venus of an ionizing factor capable of equalizing the indicated quantity of recombinations.

In Reference [5] it was shown that the existence on the earth of night ionization at the altitudes of the F layer, as well as the existence of the ionosphere during the polar night, cannot be explained without assuming the presence in the atmosphere of an ionizing agent differing from solar radiation and active during the night. A calculation of the quantity of recombinations in earth's night ionosphere derived from [22], gives $\alpha = 10^{11} - 10^{12}$ recombinations $\cdot$ cm^{-2} sec^{-1}. Therefore, an agent is active in the earth's night ionosphere that provides the same quantity of ionization. From this Danilov and Yatsenko came to the conclusion that if the same ionizing agent that is active in earth's atmosphere is also active in Venus's atmosphere, then an increase in this agent from 10 to 100 times may, with the conditions indicated, provide the required electron concentration. In a later work [26], however, Danilov and Yatsenko came to the conclusion that in order to provide the required ionization by means of a corpuscular stream, the energy density of the stream will have to exceed the corpuscular stream density in the unperturbed night atmosphere of the earth by 4 orders of magnitude.

As is known [80], the absorption coefficient in ionized gas may be presented in general form by the relationship

$$\varkappa(\lambda)=\frac{1}{2c\mu\varepsilon_0}\,\frac{4\pi e^2}{m}\,\frac{N\nu}{\omega^2+\nu^2}, \qquad \text{(IV.10)}$$

where N is the electron concentration, ν is the frequency of electron collisions, ω is the angular frequency of the received signal.

Kuz'min [56] suggested an ionospheric model of Venus in which the absorbent layer was located in the low, dense layers of the planetary atmosphere. In this case, electron collision with neutral particles plays a basic role, and the basic process of electron loss involves electron adhesion to neutral particles. Electron concentration in such a layer is defined by the relationship

$$\frac{dN}{dt}=J-\beta Nn+\gamma N^{-}n, \qquad \text{(IV.11)}$$

where J is the intensity of the ionizing agent, β is the coefficient of adhesion, γ is the coefficient of repulsion, and n is the density of the neutral particles. In a balanced system, disregarding repulsion, we have

$$N \cong \frac{J}{\beta n} \qquad \text{(IV.12)}$$

Kuz'min pointed out that under identical ionizing agent intensities and identical neutral particle densities, the electron concentration in the low atmospheric layers of Venus may be significantly higher than in earth's atmosphere, as a result of a lower coefficient of adhesion β. The fact is that the adhesive reaction of an electron to a neutral molecule with the structure of a negative ion is possible only for electrically negative molecules having a positive affinity for the electron. The molecule O_2 possesses a great positive affinity for the electron. The adhesive reaction to this molecule is the determining factor for the speed of this process and, therefore, for the coefficient β in the earth's atmosphere. According to contemporary concepts, oxygen in the lower atmosphere of earth is of biogenous origin. One may not exclude the fact that there may be no oxygen in the lower atmosphere of Venus. With carbon dioxide and possibly nitrogen on Venus, no negative ions would form. In this case the speed of adhesive reactions, i.e., the value of β, would be determined by the possible content of water vapor in /118 the atmosphere of Venus.

According to an evaluation by Strong and others [116, 117] and Spinrad [304], the relative content of water vapor in Venus's atmosphere is less than or equal to 10^{-4} - 10^{-5}, i.e., 50 - 500 times less than in the earth's atmosphere. Therefore, one may expect the quantity β in Venus's atmosphere to be 1.5 - 2.5 orders of magnitude less than that of the earth's atmosphere, and the electron density to be higher.

The difficulty in explaining the high electron concentrations in Venus's ionosphere, exceeding by several times that of the earth's ionosphere, presents a complex problem but it is still not an argument against the ionospheric model of Venus. The results of radar planetary measurements, having shown rough independence of the reflective characteristics of the planet on wavelength in the band of wavelength from 20 cm to 6 m, are more serious arguments against this model. In fact, if the radar reflection emanates from the planetary surface, then the optical thickness of the ionosphere will essentially attentuate the intensity of the reflected signal; this attentuation must increase in proportion to the square of the wavelength, introducing thereby a sharp frequency dependence into the value of the reflected signal. The assumption that reflection emanates from the planetary ionosphere, becoming critical on all waves up to 12.5 cm, requires an electron concentration in the ionosphere of Venus of approximately 10^{11} cm^{-3}, i.e., exceeding by 5 orders of magnitude that of earth.

In order to overcome these difficulties, and for agreement between the ionospheric model and radar measurement data, Kellog and Sagan [33] suggested that the ionosphere is reabsorbed during the lengthy Venusian night. Moreover, a "gap" may be formed in the ionosphere near the point opposite the Sun, through which radar operations may be conducted near the inferior conjuction. /119

Priester and others [271] suggested a cloudy structure of the ionosphere with electron densities $2 \cdot 10^9$ cm^{-3} in the clouds and $5 \cdot 10^8$ cm^{-3} between the clouds.

Kuz'min [56], Danilov and Yatsenko [24] suggested an analogous pierced model of a cloudy ionosphere.

Kuz'min drew attention to the possibility of agreement of radio-astronomic and radar measurements with a model possessing a semi-tranparent ionosphere and having an optical thickness in the centimeter band of radio waves independent of wavelength. The latter condition may be realized with sufficiently high collision frequencies, when $\nu^2 \gg \omega^2$, which occurs in the dense lower atmospheric layers.

Danilov and Yatsenko [24] also pointed out the possibility of agreement of the ionospheric model with radar measurement data, if the radiation in the 70 cm wave band is reflected from a maximum in the ionospheric layer of $N \cong 10^9$ cm^{-3}, if the radiation in the 40 cm band is fully reflected from the surface and partially absorbed within the ionosphere, and finally, if the radiation on the 12.5 cm wave is partially absorbed within the atmosphere or upon reflection from the planetary surface.

Priester and others [271] pointed out a good correlation (with an inverse relationship) between the radar distance to Venus, according to measurements made in 1961 on the 68 cm wave, and solar activity, measured in accordance with solar radio frequency radiation on the 21 cm wave. The first possible explanation is a change in the group velocity of radio wave propagation in the inter-planetary medium, connected with the emission of charged particles by the Sun. This would have to give the effect of an opposite indication. The true relation observed may be explained if one assumes that the radiation emanates not from the hard surface of Venus but from the planetary ionosphere which changes in altitude, increasing under the influence of an increase in solar activity. In this connection it is interesting to point out that the period of variations of the distance to Venus is close to the period of its revolution around the Sun. It cannot be excluded, however, that the noted variations were caused by inaccuracy in the calculation of the orbit of Venus in accordance with the ephemerides. A subsequent interpretation revealed that the indicated variations may in fact be decreased by certain changes in the orbital parameters. However, in this case the deviation between measured and calculated values are exceeded by measurement error.

Kuz'min [56] examined in a general form the possibility of interpreting an experimentally obtained spectrum of radio frequency radiation of Venus through pierced and semi-tranparent ionospheric models of Venus satisfying, as cited above, radar measurement data. /120

In order to simplify calculations a uniform case is examined for which the brightness temperature of radiation for a planet with an ionosphere having optical thickness τ and kinetic electron temperature T_e equals

$$T_b(\lambda) = T_{e0}(1-R) + b\,[T_e - T_{e0}(1-R)]\,[1 - e^{-\tau(\lambda)}], \qquad \text{(IV.13)}$$

where b is the ratio of the area of the disk covered by the ionosphere to the full area of the planetary disk. The optical thickness of a homogenous ionized layer

$$\tau(\lambda) = 5.3 \cdot 10^{-2} \frac{zN\nu}{\omega^2 + \nu^2}, \qquad \text{(IV.14)}$$

where z is the thickness of the layer. The combination (IV.13) and (IV.14) gives the analytical dependence of brightness temperature on frequency, i.e., the calculated spectrum for a given model. This spectrum is defined by three generalized parameters: $zN\nu$, T_{e0} $(1 - R)$ and $b[T_e - T_{e0}\,(1 - R)]$. Then the problem is reduced to the possibility of matching these parameters in a manner permitting the calculated spectrum to satisfy the experimental data. The calculated spectrum for $zN\nu = 4 \cdot 10^{23}$ cm^{-2} sec^{-1}, $T_{e0}\,(1 - R) = 300°K$ and $b[T_e - T_{e0}\,(1 - R)] = 280°K$ is plotted in Figure IV.7. The close conformity with experimental points, also shown on the figure, is apparent.

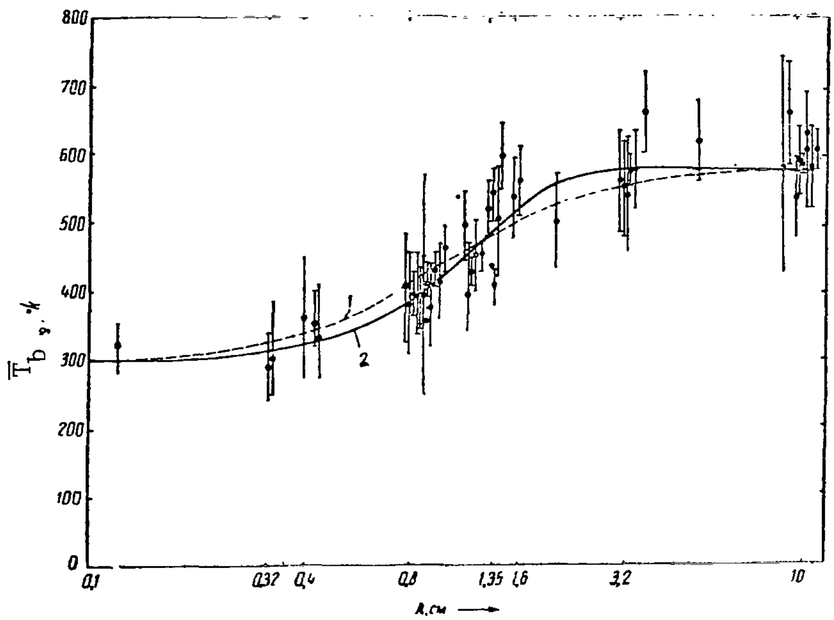

Figure IV.7. A Calculated Spectrum of Radio Frequency Radiation of Venus with a "Hot" Absorbent Ionosphere: 1) an optically thick, pierced ionosphere; 2) a semi-transparent ionosphere.

If the ionized layer investigated is located in the upper atmosphere of Venus, electron collisions occur mainly with ions. The frequency of these collisions is determined by the relationship

$$\nu_{ei} = 6{,}1 \cdot 10^{-3} \left(\frac{300}{T_e}\right)^{3/2} N_i. \qquad \text{(IV.15)}$$

Assuming for calculation that T_e = 1,000°K and considering that $N \cong N_i$, we find that in order to obtain $zN\nu = 4 \cdot 10^{23}$ cm^{-2} sec^{-1}, we must have

$$\int N^2 dz = 4 \cdot 10^{26} \text{ cm}^{-5}$$

For a semi-transparent ionosphere (b = 1) the model satisfies experimental data when $\nu = 1.5 \cdot 10^{11}$ sec^{-1}, T_{e0} (1 - R) = 300°K and $[T_e - T_{e0}(1 - R)]$ $[1 - e^{-\tau_{\omega \to 0}}]$ = 280°K. For these parameters, the calculated dependence of brightness temperature of Venus on wavelength is also shown in Figure IV.7. /121
It is apparent that for this model as well, a close conformity with the results

of the measurements is obtained.

In this manner, the problem stated concerning the possibility of satisfying experimental data through the use of an ionospheric model of Venus has, in principle, been solved positively for both a pierced and a semi-transparent ionosphere.

Tolberg and Straiton [320] suggested a model of Venus with a "hot atmosphere" differing from the ionospheric models examined above. They suggested clouds of electrically charged particles, as an electrically active medium and expressed a supposition that radio frequency radiation of Venus in the wavelength band from 8 mm to 10 cm may be explained by the redistribution of electrical charges between these particles. A similar phenomenon occurs on the earth during storms; however, maximum radiation takes place in this connection on the audio frequency band, due to the fact that the charge exchange occurs between large spaces. Tolberg and Straiton postulated that a charge exchange between separate particles may take place on Venus, and pointed out that in this case the process might explain existing experimental data concerning the spectrum of radio frequency radiation of the planet. / 122

Scarf [290] pointed out the possibility of the generation of ultrahigh frequency radiation of Venus due to plasma oscillations in its ionosphere, induced by the solar wind. His appraisal revealed that with a sufficiently weak magnetic planetary field ($<50\gamma$), and with reasonable ionospheric and solar wind parameters, it is possible to explain the high brightness temperatures of Venus measured in the centimeter wavelength band. The radiation must be generated in the ionosphere of Venus subject to illumination by the Sun and, therefore, one would expect a large amount of phase variation.

A subsequent model of Venus with a "hot atmosphere" was suggested by Vakhnin and Lebedinskiy [15]. In this type, termed the gas-discharge model by the authors, it is assumed that the high temperature radiation of Venus in the centimeter band is caused by "quiet" or "glowing" electrical discharges in a significantly large area of the upper atmosphere of the planet. These charges produce an increase in the brightness temperature of Venus by 200 - 300°K over the true thermal radiation of the planetary surface, the temperature of which is assumed to equal 340 - 400°K.

The extremely slow rotation of the planet, established by radar measurements, may be the main factor determining the development in the atmosphere of Venus of "quiet" or "glowing" atmospheric discharge, instead of the characteristic phenomena of the earth's atmosphere, which are of a stormy nature. In contrast to the earth, where air movement between warm and cold areas of the planet is greatly distorted as a result of Coriolis acceleration, on a slowly rotating planet a common movement of air masses in the form of a "breeze", i.e., a regular low-turbulence stream between the illuminated and the non-illuminated sides of the planet, must predominate, and encompasses almost the entire surface. A similar atmospheric stream in the form of a "global breeze" is, in the opinion of the authors, quite favorable for the development of an intensive "quiet" or "glowing" discharge in the upper layers of the atmosphere of Venus, due to gas electrification through friction against the hard surface and to an uninterrupted accumulation of opposite charges on the illuminated and non-illuminated sides of the planet. Inasmuch as the movement of electrons and ions is intensified with an increase in altitude, the atmosphere displays the greatest conductivity in the upper rarefied layers. Therefore, if the opposite charges are dispersed at a distance far enough to exceed by several times the altitude at which atmospheric conductivity is maximum, one may expect the appearance of an electrical current in the upper /123 layers of the atmosphere, equalizing the constant charge accumulation and creating there the effects of "quiet" or "glowing" discharge.

d) Interpretation of the Decimeter Portion of the Radio Frequency Radiation Spectrum of Venus

Recent measurements by Drake [154], Kellermann [197] and Hardebeck [180], conducted on the 11, 21, 31, 40, 48 and 70 cm waves, indicates a decrease in the brightness temperature of Venus in the decimeter relative to the centimeter wave bands (see Table III.1).

In conducting an examination analogous to that stated in § IV.1a, it may be shown that an interpretation of the "avalanche" observed in the radiation spectrum of the planet sub-surface layers colder than the surface demands a negative temperature gradient within the planetary body, which corresponds to a heat flow into the planet, and therefore contradicts physical considerations. On the other hand, in this case the interpretation of experimental data as a decrease in the radiation capability of the surface material of the planet with an increase in wavelength is not excluded. This requires that the surface of the planet consist of a dielectric with an orientational polarization having a critical wavelength near 20 cm. Viscous polar fluids are numbered among such dielectrics. The suggestion concerning the presence of the indicated frequency dependence of the radiation capability of the surface material of the planet leads to an increase in its reflective capability with an increase in wavelength, which does not contradict experimental data.

Another possible interpretation of the decrease in $\overline{T}_{b♀}$, observed in the decimeter band, consists of the absorption of this band of radio waves by the "cold" ionosphere of Venus [57].

We shall examine this possibility.

As a first approach, as was done in the earlier inonospheric model, we shall confine our examination to the uniform case. We shall assume that the ionosphere of Venus is transparent in the centimeter wave band and absorbent on longer waves. In this case a decrease in brightness temperature in the decimeter wave band requires that the kinetic electron temperature in the ionosphere T_e be lower than the brightness temperature of the surface $T_{e0} \cdot (1 - R)$. Figure IV.8 shows the calculated spectrum of the radio frequency radiation of Venus with a pierced ionosphere, plotted for T_{e0} $(1 - R) = 580°K$, /124

$zN\nu = (2 - 6)\ 10^{20}\ cm^{-2}\ sec^{-1}$ and for the cases of $b[T_e - T_{e0}\ (1 - R] = 100°K$ -200°K and -300°K, respectively. A comparison with experimental points, entered on the same figure, reveals their close congruence.

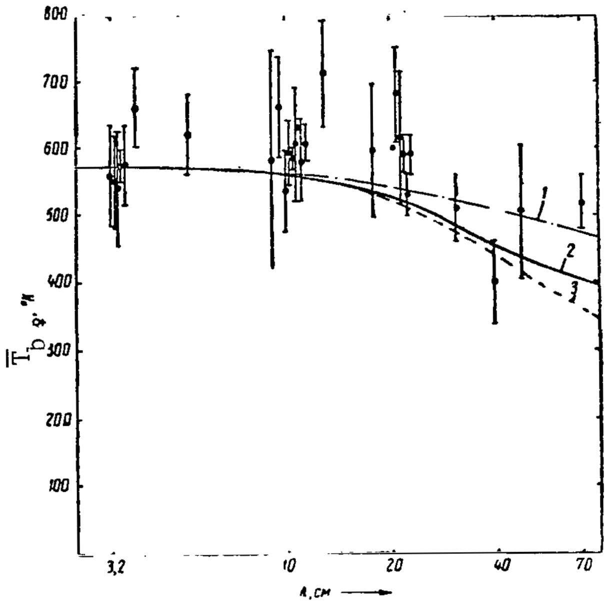

Figure IV.8. Calculated Spectrum of Decimeter Radio Frequency Radiation of Venus with a "Cold" Pierced Ionosphere: 1) $b[T_e - T_{e0}(1 - R)] = -100°K$; 2) $b[T_e - T_{e0}(1 - R)] = -200°K$; 3) $b[T_e - T_{e0}(1 - R] = -300°K$.

For a case when the absorbent layer is located in the upper atmosphere of the planet, and assuming for calculation $T_e \cong 300°K$ and the thickness of the layer z = 50 km, we obtain the required electron concentration in the layer $N \cong 10^8\ cm^{-3}$. The critical frequency of the layer $f_{cr} = 9 \cdot 10^3\sqrt{N} = 81$ MHz, corresponding to this concentration, does not contradict the results of radar measurements of Venus on frequencies 50 and 38 MHz [185, 201], due to the fact that the ionosphere is pierced in the model examined. Variations in the effective cross-section of reflection which have reached 200% have been observed in the indicated measurements. This may be the result of changes in the "porosity" of ionospheric "holes".

If the absorbent layer is located in the lower layers of the atmosphere, then the collision frequency is determined by collisions with neutral particles: /125

$$\nu_{en} = 3.6 \cdot 10^{-10} n \sqrt{T_e}. \qquad (IV.16)$$

Assuming that $T_e \cong 300°K$ and $n \cong 3 \cdot 10^{18}\ cm^{-3}$, we obtain $\nu_{en} = 2 \cdot 10^{10}\ sec^{-1}$.

When the thickness of the layer z = 10 km, this corresponds to the required electron concentration in the layer $N = (1 - 3) \cdot 10^4\ cm^{-3}$.

In the case of the semi-transparent ionosphere, required for agreement with experimental data, a collision frequency $\nu = (3 - 5) \cdot 10^9\ sec^{-1}$ may be achieved only in the dense, lower layers of the planetary atmosphere.

The calculated spectrum of radio frequency radiation of Venus with a semi-transparent ionosphere, shown in Figure IV.9, is also in close agreement

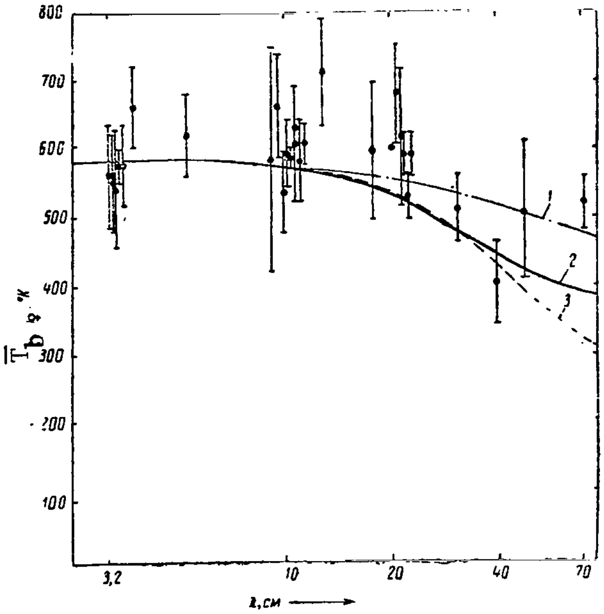

Figure IV.9. Calculated Spectrum of Decimeter Radio Frequency Radiation of Venus with a "Cold" Semi-Transparent Ionosphere:

1) $[T_e - T_{eo}(1-R)][1-e^{-\tau_{\omega\to 0}}] = -100°$ K.
2) $[T_e - T_{eo}(1-R)][1-e^{-\tau_{\omega\to 0}}] = -200°$ K.
3) $[T_e - T_{eo}(1-R)][1-e^{-\tau_{\omega\to 0}}] = -300°$ K.

with experiment. /126

A more precise definition of the parameters of the "cold" ionosphere which has been investigated requires more exact brightness temperature measurements of Venus on waves longer than 20 cm.

Finally, there is still another interpretation of the decrease in Venus's brightness temperature, suggested by Barrett and Staelin [109]. They surmised that centimeter planetary radiation emanates from the hot surface atmosphere, and that decimeter radiation is caused by the surface of the planet having a lower brightness temperature due to a low radiation capability.

2. Determination of the Nature of Radio Frequency Radiation. The Choice of a Model

The analysis presented in § IV.1 revealed that experimental data concerning the spectrum of radio frequency radiation of Venus may be interpreted within the framework of two models, which were examined above: the model with a "cold" atmosphere, and the model with a "hot" atmosphere. Both models may be consistent with radar measurement data. Therefore on the basis of spectral measurements $\overline{T}_{b♀}$ (λ) alone, the choice of a model and the determination of the physical parameters of Venus are not considered possible. The inclusion of supplementary experimental data is required. Radio-astronomic measurements of the distribution of radio brightness, the dimensions of the radiating area, and also the polarization of the radiation received from the planet furnish these data. We shall perform an analysis of these data.

a) An Analysis of the Results of the Measurement of Radio Brightness Distribution

Kellog and Sagan [33] indicated several experiments which might be of assistance in the selection of one of the alternative models of Venus. One of these experiments was the investigation of limb brightening on Venus near the 1 cm wave. The idea of the experiment consists of the fact that if radiation from Venus is caused by the planetary ionosphere, which has a higher kinetic electron temperature than the surface, then one may expect an increase in the brightness temperature of the planet on the limb, where the optical thickness on the line of sight is greater than in the center. In the case of absorption in the "cold" atmosphere, one may expect a decrease in the brightness temperature of the planet from the disk toward the limb.

However, as has already been pointed out above, such measurements conducted at the main astronomical observatory [42] of the California Institute of Technology [136], and on the space vehicle "Mariner-2" [105], revealed /127 quantitatively dissimilar results concerning the character of the distribution of radio brightness on the Venus disk.

Besides the insufficient accuracy and inconsistency in available experimental data, it should be noted that the statement of the problem does not give a uniform answer concerning the model of Venus. In fact, even in the model with a "cold" atmosphere, limb brightening may be expected in the centimeter band during an observation of the planetary surface at an angle close to Brewster's angle. Heiles and Drake [182] used this fact for an interpretation, within the framework of the "cold" model of Venus, of the limb brightening obtained by Clark and Spencer [136]. However the dielectric permittivity of the surface material $\varepsilon \cong 40$, required for agreement with experiment, is in sharp contradiction to radar measurement data of Venus.

On the other hand, darkening of the limb of the disk is also not unequivocal evidence for the use of the model with a "cold" atmosphere. In fact, it may be caused not by absorption in the "cold" atmosphere of the planet, but by a decrease in the radiation capability from the center to the limb of the visible disk for horizontal polarization. Korol'kov and others [42] interpreted their experimental data in just this way, which led them to the conclusion that the dielectric permittivity of the surface of Venus is $\varepsilon > 4$. Another possible interpretation of limb darkening may be absorption and re-emission of radiation observed in the cold atmosphere of the planet. Finally, a third interpretation of darkening of the limb is possible. In accordance to this interpretation, the radiation observed emanates from a layer, the temperature of which increases with the approach of the layer toward the surface; however, the absolute value of the temperature is by no means required to be lower than the temperature of the surface. In fact, Danilov and Yatsenko [24] examined a double-layer ionospheric model which revealed an actual decrease in brightness temperature from the center toward the limb, and only a small bright ring at a certain distance from the limb, which may not have been resolved in the experiments stated above.

With a little imagination, it is possible to devise a more complex ionospheric model wuch that we may have both brightening and darkening of the limb while maintaining an agreement with the experiments stated above.

In this way, measurements of the distribution of brightness temperature on the Venus disk have not answered the question of the mechanism of its radiation either.

Finally, measurements of the angular dimensions of the radiation area, although providing additional constraints for the model with a "hot" /128 atmosphere, do not define the nature of the radiation received. In fact, if the radiation from Venus in the centimeter band is caused, as assumed in the model with the "hot" atmosphere, by a certain electrically active medium located in the planetary atmosphere above the surface, measurements of the dimension of the radiating area may give only an evaluation of the relative altitude of the radiating medium.

Such measurements, conducted by Korol'kov, Pariyskiy, Timofeyeva, and Khaykin [42], and Kuz'min and Clark [61], revealed that the radius of the radiation area does not exceed 1.07 and 1.00 of the radius of the visible Venus disk on the 3.02 and 10.6 cm waves, respectively. This shows that the source of radio frequency radiation from Venus in these bands cannot be radiating planetary belts, which occurs, for example, in the case of Jupiter. The results of these measurements provide additional restrictions for the parameters of the ionospheric model. In order to obtain

$$\int N^2 dz = 4 \cdot 10^{26} \text{ cm}^{-5}$$

in determining the maximum altitude of the radiating layer from measurements of angular dimensions, an ionospheric electron concentration $N > 10^{10}$ cm^{-3} is required.

b) Determination of the Radiating Medium and the Choice of a Venus Model on the Basis of Measurements of Differential Polarization

One of the basic problems of Venus physics, the solution of which determines the choice between the models with a "cold" and "hot" atmosphere and therefore the temperature of the planetary surface, is the problem concerning the nature of the layer responsible for radiation in the wavelength bands from 3 to 20 cm. An investigation of the presence or the lack of differential polarization of radiation from various parts of the visible planetary disk may constitute a decisive experiment for an answer to this problem.

The idea of the experiment consists of the fact that planetary radiation must be polarized on the limbs of the visible disk if it is caused by a planetary surface having a sharp line of separation with the surrounding medium, or non-polarized if it is caused by the ionosphere, the cloud layer, or some other kind of diffuse formation without a definite line of separation. The high resolution required for this experiment may be achieved through the use of the interferometer method of observation [18].

The presence of differential polarization, which is to be expected if the radiation from Venus is caused by its surface, leads to the fact that the distribution of radio brightness on the planetary disk will depend on the polarization of the radiation received: the brightness temperature will be greater near the limbs of the disk oriented in the direction of the polarization under investigation with reference to the center of the planet than near the /129 limbs, oriented in orthogonal directions. During interferometer measurements this must lead to a dependence of the visibility function on the interferometer polarization: with an equal interferometer baseline length, the visibility function at a polarization perpendicular to the base of the interferometer, $F_{\perp}$, must be greater than the visibility function at a polarization parallel to the effective base, $F_{||}$. In the case of non-polarized radiation, caused by a diffuse formation, we may expect that $F_{\perp} = F_{||}$.

It is important to emphasize that the direction of the polarization expected is associated only with the direction of the effective base of the interferometer and, therefore, may be changed through a change in the orientation of the latter, i.e., by a change in the conditions of the experiment. This fact radically distinguishes differential polarization of the type examined from polarization caused, for example, by the planetary magnetic field (which is the case for Jupiter), i.e., in the latter case a direction of polarization is determined by the planetary parameters, and does not change with a change in the conditions of the experiment.

Kuz'min and Clark [61] conducted measurements of the distribution of radio brightness on the Venus disk in polarized radiation. The result of these measurements, presented in Figure IV.10 in the form of the difference $F_{\perp} - F_{||}$, reveals an excess of $F_{\perp}$ over $F_{||}$ substantially exceeding measurement error, which definitely establishes the fact of the presence of differential polarization of the radio frequency radiation of Venus. Therefore, the basic portion of the radio frequency radiation of Venus on the 10 cm wavelength band is thermal radiation of a medium having a sharp line of separation, i.e., the planetary surface. Hence, the model of Venus with a "hot atmosphere", in which it was assumed that the radio frequency radiation of the planet on the centimeter wavelength band is dependent not on the surface, but on a certain electrically active formation in the atmosphere of the planet, must be rejected. For further investigation it is necessary to accept the model of Venus with a "cold" atmosphere, in which a large portion of the radio frequency radiation of the planet on the 10 cm wavelength band depends upon its surface. /130

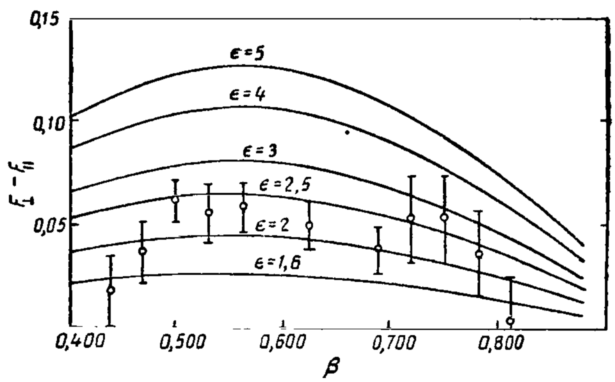

Figure IV.10. Difference Between Visibility Functions for Polarizations Perpendicular and Parallel to the Effective Base of the Interferometer.

It should be kept in mind, however, that the accepted model, as well as any model in general, is only a first approximation to the physical conditions on the planet, which in reality may prove to be more complex.

3. The Surface of Venus

a) An Evaluation of the Microrelief.

As already cited in § II.3, analysis of radar functions of reflection make it possible to form several conclusions concerning the microrelief of the planetary surface.

The diffusion component of the reflected radiation indicates the presence of areas on the planetary surface which are rough for the wavelength on which the investigation of these areas is conducted, i.e., the areas display an unevenness in microrelief significantly less than λ. The combined area of these areas, expressed in fractions of the area of the visible planetary disk, is defined by the relationship (II.113) and results in 0.126, 0.045, 0.040 and 0.062, for the 12.5, 23, 43 and 70 cm waves, respectively.

The quasi-specular component of reflected radiation indicates the presence of smooth areas on the planetary surface, large in comparison with wavelength, but inclined with reference to the average surface. The statistical properties of such a surface are characterized by the relationship (II.71 - 76). Figure IV.11 shows a distribution curve of inclinations of the flat areas indicated with respect to the average surface, obtained with the aid of (II.76) from a reflection function of Venus measured on the 23 cm /131 wave [165]. However the curve $f(\theta)$ obtained gives the distribution for only one of the vertical sections. The true inclination of any very small portion may be greater, and therefore, for determination of the average inclination, all such vertical sections must be averaged, i.e.,

$$\bar{\theta} = \frac{\int \theta F(\theta) \cos\theta \sin\theta d\theta}{\int F(\theta) \cos\theta \sin\theta d\theta}. \qquad \text{(IV.17)}$$

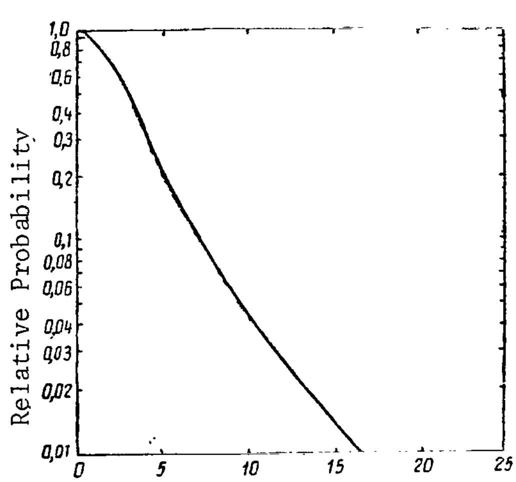

Figure IV.11. Distribution of the Surface Inclinations of Venus.

A numerical integration of the results of radar measurements on the 23 cm wave gives $\bar{\theta} = 8.2°$. This value may be somewhat understated, for in the area $\theta < 2.5°$ the reflection function $F(\theta)$ has been insufficiently investigated.

Analogous measurements for the

Moon, made by Evans and Pettengill on the 60 cm wave [164], give $\theta = 10.2°$, i.e., the unevenness of the relief of Venus is less than that of the Moon.

Carpenter [129] made an analysis of Venus measurement data on the 12.5 cm wave for the Gaussian correlation function, on the basis of a similar technique developed by Daniels [140], which led to the root-mean-square inclination of the reflecting surfaces $\bar{\theta} = 6.2°$. This also indicates a high degree of surface smoothness of Venus in comparison with the Moon.

b) An Evaluation of the Dielectric Permittivity and Density of the Surface Matter of the Planet. /132

The results of radio physical measurements of Venus make it possible to evaluate the dielectric permittivity ε and the density of the surface matter of Venus. Such an evaluation may be conducted independently on the basis of radar and radio astronomic measurement data.

The determination of ε in accordance with radar data is carried out with the aid of the relationship (II.83) in accordance with the coefficient of reflection ρ. The quantity ρ is evaluated on the basis of the effective cross-section of reflection σ_e and of investigation of the nature of the reflection. The results of the measurement of the σ_e dependence on wavelength, shown in Figure III.12, reveal that the effective cross-section of reflection is substantially identical in the wavelength band from 20 to 70 cm and decreases rapidly on shorter waves. It is difficult to explain such a sharp decrease in σ_e by frequency dependence of the reflection from the surface matter of the planet. It is more natural to assume that the nature of the dependence $\sigma_e(\lambda)$ observed is caused by absorption in the atmosphere of Venus. Allowing for the double passage of the radar signal through the planetary atmosphere, the optical thickness τ of the latter in this case must be 0.13 and 1.4 on the 12.5 and 3.6 cm waves, respectively. Such an assumption does not contradict the conclusion reached above that on the 10 cm wavelength band the radio frequency radiation from Venus received on the Earth is principally planetary surface radiation, since on the 10.6 cm wave the optical atmospheric thickness in this case will be only 0.22. There is a possible contradiction in the values of τ (estimated above in accordance with the decrease in σ_e with a shortening of the wave) required for the realization of Venus's radiation spectrum, obtained within the framework of the accepted planetary model with a "cold" atmosphere (see Figure IV.3). The possible contradiction may be eliminated by assuming the presence of two absorbent layers in the atmosphere of Venus. The first is a "cold" upper layer, defining the radio frequency radiation spectrum of Venus but exerting no influence on radar measurements obtained since even for 3.6 cm, the shortest wave that radar measurements were carried out on, the absorption in this layer was negligibly small. The second is a lower surface layer which absorbs the radar signal, but renders no substantial influence on the value of the planetary brightness temperature measured since the temperature of this layer is close to the surface temperature.

As has already been pointed out earlier, it is usually assumed in interpreting radar measurement data that the reflected radiation consists of only two components: the quasi-specular and the diffuse. In this case the /133 calculation, accomplished with the aid of (II.91), leads to values for the surface reflection coefficient ρ of 0.141, 0.147 and 0.127 on the 23 cm, 43 cm, and 70 cm waves, respectively. The average of these measurements $\bar{\rho} = 0.138$ corresponds to the dielectric permittivity of the surface material $\varepsilon = 4.7$. In accomplishing this calculation, it was assumed that $b_{sp} = 1 - b_d$, i.e., that any reflection not satisfying the condition of diffuse reflection is quasi-specular. It is apparent that this assumption is only a first approximation and that the transition between diffuse and quasi-specular reflection must proceed smoothly, i.e., there must exist on the characteristic curve of reflection an intermediate area between the diffuse and quasi-specular; in allowing for this, we have for convenience termed the reflection from this area "scattered", and the coefficient of reflection ρ is linked with the parametric measurements σ_e and b_d by the relationship (II.94). It is also apparent that $1 - b_d = b_{sp} + b_s$.

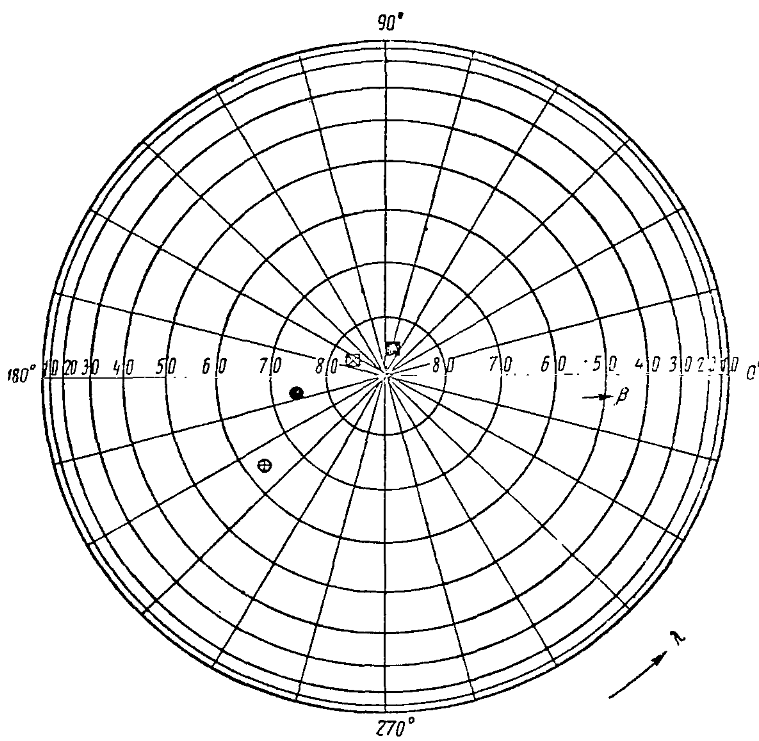

Figure IV.12. Orientation of the Poles of Venus: ⊕ - is the pole of "coldness" according to polarization measurements [61]; • - is the pole of "coldness" according to measurements of the asymmetrical distribution of the brightness temperature [61]; ⊠ - is the pole of rotation according to radar measurements at the Jet Propulsion Laboratory; ■ - is the pole of rotation according to radar

The question concerning the relationship between b_{sp} and b_d demands special investigation. However, for the next approach, it seems reasonable to assume that the energy of the scattered component of the reflected radiation is 2 - 4 times less than the energy of the quasi-specular component. In this case

$$b_s \cong \left(\frac{1}{3} - \frac{1}{5}\right)(1 - b_d)$$
$$b_{sp} \cong \left(\frac{2}{3} - \frac{4}{5}\right)(1 - b_d)$$

and the calculation according to the formula (II.94) under the assumption that the directional coefficient of the scattered component is an average between the directional components of the quasi-specular and the diffuse components

$$g_s = \frac{1}{2}(g_{sp} + g_d) = \frac{11}{6}$$

gives the average value $\bar{\rho} = 0.11 - 0.13$, which corresponds to $\varepsilon = 4 - 4.5$. In an extreme case, when the quasi-specular component is completely absent and all of the non-diffuse reflection is scattered, $\bar{\rho} = 0.080$ which corresponds to $\varepsilon = 3.15$.

Thus, according to radar measurement data, the dielectric permittivity of the surface matter of Venus falls within the limits $\varepsilon = 3.15 - 4.7$, while the most probable value is $\varepsilon = 4 - 4.5$.

In order to evaluate ε according to radio astronomical measurement data, it is possible to utilize the fact of the dependence on ε of the differential polarization of the radiation from Venus and, therefore, the difference in the planetary visibility functions at polarizations perpendicular and parallel to the base of the interferometer, $F_\perp - F_{||}$.

The calculated dependence $F_\perp - F_{||}$ for various ε is shown in Figure IV.12. The results of differential polarization measurements of the radio frequency radiation from Venus on the 10.6 cm wave [61] have also been entered on the same figure. The closest agreement of experimental data with calculations occurs with $\varepsilon = 2.2 \pm 0.2$.

However, the quantity ε obtained in this manner characterizes the radiation of a smooth planet with a transparent atmosphere. But it was shown above that for the 10.6 cm wave, the planetary surface is partially rough, and its atmosphere is possibly partially absorbent. Therefore, it is necessary to calculate the influence of these factors on the difference $F_\perp - F_{||}$

already investigated, and to introduce a corresponding correction into the determination previous of the value ε.

We shall make an estimate of the influence of the rough planetary surface on the basis of radar measurement data. We shall stipulate here for simplicity that the quasi-specular and the diffuse components of the reflected signal are due to reflection from various areas of the planetary surface of Venus, which are either completely smooth or completely mat.

Since the radiation of a mat surface is non-polarized, in this case one may expect a decrease in polarization by $1/(1 - a_d)$ times*. For Venus near the 12.5 cm wave, $a_d = 0.125$, and therefore the true polarization is 15% greater than the measured value. This correction gives an increase in the dielectric permittivity of $\Delta\varepsilon_1 = 0.2$.

The influence of absorption in the atmosphere, analogous to the influence of roughness, also leads to a decrease in polarization. The value of this reduction is e^{τ} times. However, in connection with the fact that the polarized radiation emanates not from the center, but from the limb of the visible disk of the planet, the quantity τ will be greater than the atmospheric optical thickness in the center of the disk τ_0. In an approximation of a plane atmosphere, $\tau = \dfrac{\tau_0}{\cos\theta}$, where θ is the angle between the direction to the observer and the perpendicular to the planetary surface. Maximum polarization will be near angles θ close to Brewster's angle

$$\theta_b = \arctan\sqrt{\varepsilon}. \tag{IV.18}$$

When $\varepsilon = 3$, $\theta_b = 60°$ and $\cos\theta = 0.50$. Assuming, according to radar data, /135
that $\tau_0 = 0.23$, we obtain $\tau = 0.46$ and $e^{\tau} = 1.58$. This correction results in an increase in the dielectric permittivity $\Delta\varepsilon_2 = 1.1$.

In order to calculate large-scale variations from the spherical surface, we shall assume that the areas responsible for quasi-specular reflection are formed from small areas, comparatively large with respect to wavelength, with diverse angles of inclination. A correction for the influence of these variations, calculated in [61], is $\Delta\varepsilon_3 = 12\,\overline{\alpha^2}$, where $\overline{\alpha^2}$ is the average square of the angle of inclination of the planetary surface. Assuming, in agreement with [129], that $\overline{\alpha^2} = 0.012$, we obtain $\Delta\varepsilon_3 = 0.14$.

Allowing for all of the indicated corrections, the value of the dielectric permittivity, evaluated in accordance with polarization measurements, increases to $\varepsilon = 3.6$, which agrees well with the corresponding evaluation obtained through the results of radar measurements. The value ε obtained is satisfied

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* The meaning of the parameter a_d was clarified on page 48.

by dry silicate rocks of the same type as dry sand, granite, basalt, diorite, dunite, [51], limonite [263] and other dry rocks of a terrestrial type.

The data obtained do not make it possible to answer the question of whether the surface of Venus is solid or liquid. However, such a liquid could not be water, which has a significantly lower boiling point and a significantly higher dielectric permittivity than what we have determined for the planetary surface. Several oily-type fluids satisfy the physical conditions on Venus. However, the hypothesis that the surface of Venus is an oil ocean, seems false. Moreover, radar measurements, having shown stable formations on Venus with reflection characteristics differing from the remainder of the planet, apparently testify against the assumption that the entire surface of the planet is liquid.

It is more probable that the surface of Venus is mainly solid. If this assumption is correct, then the results obtained make it possible to evaluate the density of the surface matter of Venus. This evaluation is based on the empirical dependence of the density ρ on the dielectric permittivity ε.

$$\rho \cong \frac{\sqrt{\varepsilon}-1}{0.5},$$

obtained by Krotikov [49] for various dry terrestrial rocks. For Venus $\varepsilon = 3.6$, which corresponds to $\rho_{♀} = 1.8 \text{ g} \cdot \text{cm}^{-3}$. The value obtained is close to the /136 density for terrestrial surface rock $\rho_{♁} = 2 \text{ g} \cdot \text{cm}^{-3}$. This also forms a basis for suggesting that the surface matter of Venus may be analogous to dry terrestrial surface rocks.

c) Surface Temperature and its Planetary Distribution

(1) Ambiguity in Brightness Temperature Distribution. The Detection of "Cold" Areas of the Planet.

The positional angle of the effective base of the interferometer χ, and therefore the direction in which the investigation of the distribution of radio brightness is carried out, depends on the orientation of the base of the interferometer and on the position of the source on the celestial sphere (see Figure II.14). This circumstance makes it possible to investigate the presence of central symmetry of the brightness temperature distribution on the visible disk of the planet. With a lack of central symmetry, as indicated in § II.1, it could be expected that the integrated planetary radiation would be in part linearly polarized. Thus a measure of linear polarization of the integrated radiation allows an independent investigation of the nature of the symmetry of the brightness temperature distribution by another method.

The dependence of the planetary visibility function, with central asymmetric distribution of brightness temperature, on the positional angle of the effective base of the interferometer, is determined by the relationship

(II.60). With orientations of the base of the interferometer in the directions east-west (EW) or north-south (NS), i.e., the directions must often taken, the dependence of the spatial frequency β on hour angle t is an even function. Then, a comparison of two measurements conducted with identical hour angle values (and therefore with identical β), to culmination ($F_{t<0}$) and after transient ($F_{t>0}$) from the relationship

$$\delta \sin \Phi = \pm \frac{F_{t>0} - F_{t<0}}{2H(\beta) \sin (\chi_{t>0} - \chi_{t<0})} \tag{IV.19}$$

reveals that it is not difficult to determine a generalized parameter δ of the temperature distribution which characterizes central asymmetry (see page 37), and also to calculate the angle Φ which gives the direction of this asymmetry. The sign "+" in the formula (IV.19) corresponds to the NS base and the sign "-" to the EW base.

Measurements by Kuz'min and Clark [61] revealed an essential difference between $F_{t>0}$ and $F_{t<0}$, significantly exceeding measurement errors. Independent measurements of the polarization of radio frequency radiation, /137 conducted by Seielstad and others [293] and Kuz'min and Clark [61], also testify in favor of the lack of central symmetry in the brightness temperature distribution on the visible disk of Venus. The value of the asymmetry corresponds to the generalized parameter $\delta = 0.25 \pm 0.05$. The relationship of this parameter with the magnitude of the asymmetrical component on the limb, shown in Table II.1, reveals that in the models of temperature distribution examined in § II.2, the temperature of the "cold pole" is 25-30% less than that of the equatorial limb of the visible disk of Venus. The coordinates of the north "cold pole" of Venus have been defined as $\lambda_p = 192°$; $\beta_p = 74°$ or $\alpha_p = 15^h\ 52^m$; $\delta_p = 59°$ according to measurements of the dependence ($F_{t>0} - F_{t<0}$) on the orientation of the effective base of the interferometer, and /138 $\lambda_p = 213°$; $\beta_p = 64°$ or $\alpha_p = 15^h\ 52^m$; $\delta_p = 47°$, according to polarization measurements. Figure IV.12 shows a comparison of the position of the "cold pole" of Venus with the position of the poles of planetary rotation, as determined from radar measurement data. This comparison reveals that the "cold" poles of Venus are located near the poles of rotation and, therefore, that the areas of reduced brightness temperature are the polar areas of the planet. Interferometer investigations of the distribution of the brightness temperature in the equatorial direction [61], measurements of phase variation, and direct comparisons of the brightness temperature of the non-illuminated side of Venus and the side illusminated by the Sun, indicate an insignificant change in surface temperature with a change in longitude, and a small temperature difference between the day and night sides of the planet.

(2) A Determination of the Radius of the Planetary Surface.

The results of optical measurements of Venus were stated in § 1.2. Due to the non-transparence of the cloud layer, these measurements do not make it possible to determine the radius of the surface of the planet. Measurements of this nature are possible through the transparent window in the radio wave band. However, radiotelescopes currently available and under construction do not have the required resolving power for such an experiment. Therefore at the present time and in the foreseeable future measurements of the radius of the surface of Venus are possible only with the aid of radio interferometer technology.

The first measurements of this type based on the transparent window of Venus's atmosphere were carried out by Kuz'min and Clark [61]. The experiment was based on a measurement of the value of the spacial frequency β_0 (see page 20), where the interferometer visibility function F vanishes. With a known distribution of radio brightness, it is possible to determine $r_♀$ through (II.13) and (II.54). The results of these measurements revealed that the radius of the surface of the planet $r_♀ = 6060 \pm 55$ km, i.e., 40 km less than the ephemeris radius of Venus and 60 km less than the radius of the planet with the cloud layer.

The result obtained corresponds closely with radar measurements of Venus conducted by Kotel'nikov and others [45], who obtained the closest agreement between calculation and experiment with the assumption that the radius of Venus is 80 km less than the ephemeris radius. Preliminary data from radar measurements at Arecibo [159] also indicates that the radius of Venus is less than the ephemeris radius.

(3) A Determination of the True Surface Temperature. /139

The parameters ε, δ, Δ, $r_♀$ and τ obtained above, in combination with the results of measurements of the brightness temperature of Venus $T_{b♀}$, averaged in accordance with the visible disk of the planet, make it possible to determine the true temperature of the surface. Calculated results are based on the principle of a decrease in temperature from the equator to the poles. For the four forms of temperature distribution examined in § II.2, the surface temperature is $T_{\bullet} = 650 \pm 70°$ K at a point opposite the Sun and approximately 150°K lower in the areas near the poles.

The true temperature defined above refers, strictly speaking, not to the surface of the planet itself, but to a certain layer located at the depth of penetration of the electromagnetic waves, and responsible for the radio frequency radiation observed.

We shall calculate the depth at which this layer is located, and the possible temperature difference between this layer and the planetary surface.

In agreement with [51], the depth of penetration of the electromagnetic wave is

$$l_e = \frac{\lambda}{2\pi\ (\tan\Delta/\rho)\,\rho\sqrt{\varepsilon}}, \qquad \text{(IV.20)}$$

where $\tan\Delta$ is the tangent of the loss angle, ρ is the density and ε is the dielectric sonstant of the surface matter. We estimated the quantity ρ above as 1.8. Assuming $\tan\Delta \simeq 10^{-2}$ for silicate rocks in agreement with [51], we obtain for λ = 10.6 cm the depth of penetration of the electromagnetic wave l_e = 88 cm. Further, we shall accept the temperature gradient in the soil of the planet as equal to that of Earth, grad T = 0.025 grad $\cdot$ m^{-1}. Then, the difference in temperature between the radiating layer and the planetary surface is

$$T_{e0} - T_{ps} = l_e \,\mathrm{grad}\, T \cong 0{,}02^\circ. \qquad \text{(IV.21)}$$

Thus, for the surface composition of Venus, similar to that of Earth, T_{e0} = = T_{ps}. The difference in T_{e0} and T_p does not exceed measurement errors even by three magnitudes with a change in the component parameters of (IV.20) and (IV.21). In practice, therefore, we may consider that the temperatures determined above are the true temperatures of the surface of Venus.

(4) Concerning the Mechanism of Surface Heating.

The problem of surface heating in the maintenance of high surface temperatures is one of the problems of the physics of Venus which is not at all clear.

A calculation of thermal balance in the presence of the solar radiant en- /140
ergy and of radiation losses lead to an equilibrium temperature at a subsolar point.

$$T_0 = \sqrt[4]{\frac{E_{sol}(1-A)}{\sigma\Delta^2}} = \frac{394\,(1-A)^{1/4}}{\sqrt{\Delta}}. \qquad \text{(IV.22)}$$

Here E_{sol} is the solar constant 1.37 $\cdot$ 10^6 erg $\cdot$ cm^{-1} [2], σ = 5.67 $\cdot$ 10^{-5} erg $\cdot$ cm^{-2} deg^{-4} sec^{-1}, a constant in Stefan's radiation formula, A is the albedo of the planet, Δ is its distance from the Sun expressed in fractions of an astronomical unit.

For a rotating planet with uniform thermal energy distribution on the planetary surface, the equilibrium temperature is

$$T_0 = \sqrt[4]{\frac{E_{sol}(1-A)}{4\sigma\Delta^2}} = \frac{278\,(1-A)^{1/4}}{\sqrt{\Delta}}. \qquad \text{(IV.23)}$$

The calculated temperature of Venus, with an albedo of 0.7 for a rotating planet, is only 240°K. The presence of an atmosphere changes the thermal balance of a planet. This change consists of the fact that the atmosphere partially suppresses both the direct solar radiation and the characteristic radiation of the planetary surface. In connection with the different spectral characteristics of these radiations, the attenuation of these radiations by the atmosphere may also be different. Moreover, when an atmosphere is present, the planetary surface receives additional exposure; first, as a result of solar radiation dispersed by the atmosphere, and secondly, as a result of characteristic thermal radiation of the atmosphere. A combination of these processes may either reduce the temperature of the surface or raise it. The latter case is associated with the so-called "greenhouse effect" and occurs if the components making up the atmosphere of the planet have bands of absorption in the far-infrared portion of the spectrum, at which maximum characteristic atmospheric radiation occurs.

Under such conditions, the stream of solar radiation passes through the radiation-transparent atmosphere to the surface of the planet with only a small amount of attenuation, whereas the characteristic surface radiation is absorbed to a significant degree by the atmosphere and is reradiated back to the surface.

The indicated greenhouse effect, caused by the presence in the atmosphere of carbon dioxide and water, occurs on the Earth, increasing the average temperature of the Earth by approximately 50°K in comparison to the equilibrium temperature 245°K.

In connection with the fact that the atmosphere of Venus contains a significantly larger quantity of CO_2 than the Earth's atmosphere, it might be expected that the greenhouse effect on Venus would be more pronounced.

A significant decrease in the albedo of the planet on waves longer than 3 μ apparently indicates a high degree of absorption in the planetary atmosphere in the band of its characteristic thermal radiation, and also attest to the presence of the greenhouse effect on Venus. /141

Wild [331] made the first calculation of the thermal balance of Venus's surface allowing for the greenhouse effect. Accepting that the planetary atmosphere contains (2 - 4) $\cdot$ 10^4 atm $\cdot$ cm CO_2, with a planetary albedo of 0.60, he calculated a surface temperature of 408°K.

A subsequent evaluation of the greenhouse effect on Venus was made by Sagan [278, 279], on the basis of a solution to the radiation balance equation

$$\sigma T_0^4 = \sigma T_a^4 - (1 - \alpha)\,\sigma T_{ps}, \qquad \text{(IV.24)}$$

where T_0 is the equilibrium radiation temperature, T_a is the temperature of the atmospheric layer responsible for the absorption of the characteristic radiation of the planet, α is the average value (according to the spectrum) quantity of this absorption, and T_{ps} is the temperature of the planetary surface. Having determined that T_0 = 254 and 240°K for a planetary albedo A = 0.64 and 0.71, respectively, and assuming T_a = 234°K in agreement with [295], Sagan estimated the averaged absorption required to heat the planetary surface, through the greenhouse effect, to a temperature $T_p = 600°K$. The calculation revealed that 99.5% of the planetary radiation must be absorbed by the atmosphere, i.e., the optical thickness of the atmosphere in the band of characteristic infrared radiation of the planet must equal 5.

Assuming that the atmosphere of Venus consists mainly of carbon dioxide, and assuming 10^5 atm • cm CO_2 in the layer above the clouds in agreement with [41, 102], Sagan estimated the full CO_2 content in the atmosphere as $1.8 \cdot 10^6$ atm • cm for a planetary atmosphere in a state of convectional equilibrium. However, the indicated quantity of CO_2 proved to be insufficient to create a required greenhouse effect, due to the transparence of such an atmosphere on waves longer than 18 μ. In order to close this window, Sagan suggested the presence in the atmosphere of Venus of some other molecule, absorbent in this band, and in this capacity he offered the water molecule. The required water vapor content in the atmosphere of Venus must reach 9 g • cm^{-2} suggested for a synchronously rotating planet.

Plass and Stull [260] calculated the absorption in carbon dioxide at high pressures (to 31 atm) and at CO_2 levels up to $2.3 \cdot 10^7$ atm • cm, and also accepted these results as an evaluation of the heating of Venus due to the greenhouse effect. Assuming on the basis of [278] that the required attenuation of infrared radiation of the planetary surface equals 99%, they concluded /142
that a surface temperature of Venus of 600°K may be explained by a greenhouse effect in the atmosphere in which infrared absorption by carbon dioxide occurs if the quantity of atmospheric carbon dioxide reaches $2 \cdot 10^7$ atm • cm. This figure, in their estimation, corresponds to a pressure of 60 atm at the surface. In this case the CO_2 transparent window is closed as a result of the broadening of spectral lines by pressure.

Thaddeus [316] came to an analogous conclusion.

The calculation of the required absorption conducted by Sagan is rather course, for it is based on the use of the small difference between T_0 and T_a and is therefore very critical with respect to a small change in these values, in conjunction with the coarseness of the model used for calculation of T_0 and the experimental inaccuracy in the determination of T_a. Thus, in considering Sinton's [296] review of the bolometric albedo of Venus, from (IV.24) we obtain an absorption of over 100%, which has no physical significance.

A more concrete examination of this question was made by Jastrow and Rasool [186, 187]. Proceeding from a solution to a transport equation analogous to [4] in the form

$$T_{ps}^4 = T_0^4\left(1 + \frac{3}{4}\tau\right), \qquad \text{(IV.25)}$$

where T_{ps} and T_0 are the surface temperature and the equilibrium temperature of Venus, respectively, they revealed that for the atmospheric optical thickness $\tau = 5$, determined by Sagan, the planetary surface is heated to only 340°K. To obtain T_{ps} = 600°K, τ = 42.5 is required, which demands a completely different absorbend agent than that suggested by Sagan.

Recently Sagan [286] reviewed his work utilizing the relationship (IV.25). He came to an analogous conclusion that in order to obtain a surface temperature T_{ps} = 700°K in the model which he examined, an atmospheric optical thickness in the infrared radiation band of the planet $\tau \approx 100$ would be required. This could not be provided by 10^6 atm · cm CO_2 and 9 g · cm^{-2} of water vapor.

The aforesaid studies of the greenhouse mechanism for the surface heating of Venus were conducted without considering the influence of the planetary cloud layer. However, such disregard is not considered well-founded. In fact, infrared measurements of Venus, conducted by Chase, Kaplan, and Naugebaur [135] through the space probe "Mariner-2" in two spectral intervals, revealed identical brightness temperatures. These intervals were 10.2 - 10.5 μ and 8.1 - 8.7 μ; the first interval fell within the band of absorption, and the second, within the CO_2 transparent window. This indicates that the radiation /143 was caused, apparently, by the clouds of Venus being optically thick in the infrared band.

As is known [94], clouds on the Earth increase the greenhouse effect. In this connection, it seems necessary to consider the effect of the clouds on the temperature balance of Venus.

Ohring and Mariano [247] were the first to take this into account. They examined a case involving Venus's cloud layer,as completely transparent in the visible portion of the spectrum and completely non-transparent in the infrared band. The greenhouse effect was maximum when the vertical temperature gradient in the atmosphere was equal to the adiabatic.

The calculation revealed that the clouds greatly increase the greenhouse effect, and significantly reduce the atmospheric non-tranparence required. Thus, for example, for an atmosphere consisting of 5% CO_2 and 95% N_2, if the clouds cover 99% of the planetary surface then surface heating up to a temperature of 650°K, due to the greenhouse effect, requires an optical atmospheric thickness in the infrared band of approximately 5; this may be achieved with 10^6 atm · cm CO_2 and several g · cm^{-2} of water vapor. The latter does not contradict the abundance of water vapor, measured by Bottema, Plummer and Strong [116], and Dolfuss [148] above the cloud layer, if the pressure near the planetary surface is several tens of atmospheres. An increase in brightness temperatures and pressures in the radiating layer of Venus, as obtained by Spinrad [302] on 7,820 Å and Kuiper [209] on λ = 1.0 - 1.7 μ in comparison with data obtained in the band 3.75 - 14μ, is an indication apparently in favor of an increase in the transparency of Venus's cloud layer in the visible and near-infrared areas. This supports the basic premise of the mechanism of Ohring and Mariano.

Sagan and Pollack [286] also examined the greenhouse heating of Venus through the participation of the cloud layer, and thoroughly analyzed conditions under which the cloud layer might provide required conditions, i.e., pass solar radiation in the visible and near-infrared areas and remain non-transparent in the band of characteristic planetary radiation. The analysis revealed that the required cloud characteristics may be obtained as the result of frequency dependence on the index of dispersion if the clouds consist of particles of matter approximately 1 μ in radius with a high reflective capability and with a relatively low refractive index ($n_1 \sim 1.4$). These parameters agree also with Lyot's measurements [223], and do not contradict the parameters determined above for the aerosol, which satisfies the observed /144
spectrum of Venus's radio frequency radiation.

Sagan and Pollack also pointed out that if Venus's atmosphere is in a state of convectional equilibrium, and even if the clouds absorb a significant portion of solar radiation, the absorbed energy may be conveyed downward by means of a convectional stream toward the surface of the planet, and also become a source of heat.

Another source of planetary surface heating, suggested by Opik [250], was designated the "aeolospheric" model. According to this model, Venus's atmospheric layer under the clouds is a heavily dust-laden area of strong winds circulating between the cloud layer and the surface; surface heating occurs through wind friction of dust particles. The dust itself creates non-transparence for characteristic infrared planetary radiation. Wind energy is replenished as a result of solar radiation, which is absorbed in the planetary cloud layer.

However, Sagan and Pollack [286] revealed that for an atmosphere in a state of convectional equilibrium, the convectional stream itself, and not wind friction, is the basic source of energy transfer from the cloud layer, which absorbs solar radiation, to the warmed surface. In this case, the heating mechanism is reduced to the aforesaid investigation conducted by Ohring and Mariano as well as by Sagan and Pollack.

In the aforesaid studies of the "greenhouse" and "aeolospheric" models, solar radiation is the source of planetary surface heating. Kuz'min [57] pointed to internal planetary warmth as another possible source of heating.

In summarizing that which has been stated above, it may be said that the explanation of the high surface temperatures on Venus by means of the greenhouse effect apparently agrees with available observation data concerning this planet and seems most probably; however, the conclusive solution of this problem must be accomplished after more complete information concerning Venus's atmosphere is obtained, in particular a clarification of data concerning the content of water vapor in the atmosphere, a determination of the composition of the cloud layer, and an evaluation of internal planetary heat should be effected.

4. The Atmosphere of Venus

The theory of planetary atmospheric composition has been stated in a number of works (see for example [94]). Sharonov [96] examined this problem as it applies to Venus's atmosphere.

In an anology with the composition of the Earth's atmosphere, it may be assumed that Venus's atmosphere is divided naturally into the four following layers: /145

1) the troposphere, which is characterized by convectional gas agitation, by a monotonic decrease in temperature with altitude, and by the presence of condensation in the form of clouds;

2) the stratosphere, which is characterized by the lack of convection and monotonic temperature variation;

3) the ionosphere, which consists of an ionized rarefied gas;

4) the exosphere which is the most rarefied upper layer where separate molecules achieve speeds surpassing the critical value and leave the celestial body.

The problem of the theory of the planetary atmospheric composition consists of determining the distribution of density ρ, pressure p, and temperature T in relation to altitude h above the planetary surface. The relationship between the gas characteristics indicated above are expressed by the equation of state

$$p = \rho \frac{R}{\mu} T, \tag{IV.26}$$

where μ is the molecular weight, and R is a gas constant.

With a shift from altitude h to altitude h + Δh, the change in pressure is equal to the weight of the gas included in the elementary layer dh, which is equal to gρdh. Therefore the basic atmospheric equilibrium equation reduces to the equation

$$dp = -g\rho dh. \tag{IV.27}$$

Dividing (IV.27) by (IV.26), we obtain

$$\frac{dp}{p} = -\frac{\mu g}{RT} dh. \tag{IV.28}$$

In order to integrate this equation, we must have the relationship between ρ and h, which is unknown. Therefore, the calculation is usually effected for several of the most simple hypothetical models of the composition of the atmosphere; in particular, $\mu=$ const (the chemical composition of the atmosphere is identical at all altitudes).

The composition of the troposphere is closest to a polytropic model of atmospheric composition, in which a linear change of temperature with altitude is assumed:

$$T = T_{ps} + \beta h, \tag{IV.29}$$

where T_{ps} is the temperature at the planetary surface, $\beta = \frac{dT}{dh}$ is the temperature gradient. In this case integration (IV.28) gives

$$\frac{p}{p_{ps}} = \left(\frac{T}{T_{ps}}\right)^{\frac{\mu g}{\beta R}}, \tag{IV.30}$$ /146

where p_{ps} is the pressure at the planetary surface.

The model of an adiabatic atmosphere is usually employed to obtain a quantitative evaluation of the tropospheric parameters. The model of the adiabatic atmosphere represents a particular case of a polytropic atmosphere, which corresponds to the adiabatic process. The temperature distribution is determined through adiabatic cooling of gas as a result of expansion with an increase in altitude. The adiabatic temperature gradient β_a, which corresponds to this case, is defined by the formula

$$\beta_a = \frac{Ag}{C_p}, \tag{IV.31}$$

where $A = 2.38844 \cdot 10^{-8}$ cal $\cdot$ erg^{-1}, which is the heat equivalent of work, $g = 835$ cm $\cdot$ sec^{-2}, which is the acceleration of gravity at the surface of Venus, C_p is the specific heat of the gas at a constant pressure.

A change in pressure with altitude in an adiabatic atmosphere is described by the formula

$$\frac{p}{p_{ps}} = \left(\frac{T}{T_{ps}}\right)^{\frac{\gamma}{\gamma-1}}, \tag{IV.32}$$

where $\gamma = C_p/C_v$, which is a specific heat ratio at a constant pressure and at a constant volume.

We have at our disposal available data concerning the temperature of the planetary surface, obtained from radio astronomical measurements (§ IV.3).

The atmospheric temperature of Venus at the level of the cloud layer is also known from optical measurements (§ 1.4). Since we know the pressure at the level of the cloud layer (§ 1.3) from optical data, we may, with the aid of (IV.32), estimate the pressure at the planetary surface. From the obvious relationship

$$h_{cl} = \frac{T_{cl} - T_{ps}}{\beta} \qquad \text{(IV.33)}$$

we may also estimate the altitude of the cloud layer above the planetary surface.

However, the chemical composition of Venus's atmosphere, and therefore the value of the adiabatic gradient, are not known. As indicated above, the basic component of the atmosphere is, apparently, nitrogen or inert gases. For nitrogen, γ = 1.404 and β_a = 8 deg · km^{-1}. For argon, γ = 1.67 and β_a = /147
= 16 deg · km^{-1}. With T_{ps} = 650°K and T_{cl} = 240°K, this means the altitude of the cloud layer is 50 or 25 km for a nitrogen or an argon atmosphere, respectively. This agrees with the determination made by Kuz'min and Clark [61] that the planetary surface radius is 6,060 km, and with optical data defining the radius of the cloud layer [324]. Planetary surface pressure p_p, in two cases examined, was greater than the pressure at the level of the cloud layer by 32 and 12 times. Accepting that the latter equals 90 mb or 300 mb, we may estimate the surface pressure at 3 - 10 atm. Since it is doubtful that the temperature gradient exceeds the adiabatic, the estimate made for the surface pressure is, apparently, a minimum. With a gradient lower than the adiabatic, the value p_p increases.

An estimate of the possible content of water vapor in the lower atmosphere of Venus, conducted by Drake [155] on the basis of a lack of a discernible line of absorption λ = 1.35 cm, establishes an upper limit of water vapor content in Venus's atmosphere equal to several tens of grams of precipitated water per square centimeter.

5. Elements of Rotation of Venus

A determination of the elements of rotation is one of the important problems of planetary investigation. Knowing the alignment of the rotational axis, we may point out the position of the poles, the equator, and the network of meridians and parallels on the planetary surface.

The most dependable data concerning the elements of rotation of Venus have been obtained from radar measurements. Rotational direction of the planet around its axis is the reverse of the revolution of the planet in its orbit around the Sun. The true or sidereal rotational period of the planet is 245 ± 3 Earth days, which corresponds to the length of a solar day on Venus equal to 118 Earth days.

Goldreich and Peal [335] (sic) directed attention to the fact that if the moment of inertia of Venus depends on direction, a stable system of planetary rotation is possible in which at the inferior conjuction Venus is always oriented in such a manner that its moment of inertia is at a minimum with respect to the direction toward the Earth.

In order to obtain such an earth-sychronized rotation, Venus's rotational period T must be connected with the synodical period of planetary revolution T_c by the relationship

$$T = \frac{T_c}{n + \Psi/360^\circ}, \qquad \text{(IV.34)}$$

where n is an integer , $\Psi = 145^\circ$, which is the difference (in the retrograde direction) of the ecliptical longitudes of two consecutive inferior con- /148
junctions of Venus. When n = 2, this corresponds to a rotational period for Venus T = 243.6 days, which, within the accuracy of measurement error, agrees with experiment. This agreement would be even better, if we consider the fact that the surface radius of Venus, as measured by Kuz'min and Clark [61], was somewhat less than the ephemeris, on the basis of which the determination of the apparent angular velocity of the rotation of the planet was conducted. In order to clarify these interesting questions, further more precise experimental determinations of the rotation period in the radius of Venus are required.

The alignment of Venus's rotational axis is close to the orbital pole of the planet ($\alpha = 276^\circ$, $\delta = 66^\circ$); the inclination of the planetary pole from the orbital pole does not exceed 6°.

In principle, analogous to Earth, one may expect a change in the position of the poles with time due to precession and nutation. However, nutation is quite small, and precession takes place very slowly. Therefore, in practice, one may consider the position of the poles on the planet to be unchanging.

CHAPTER V

THE PROSPECTS OF FURTHER RADIO PHYSICAL INVESTIGATIONS OF VENUS

As shown above, the employment of radio physical methods of investigation /149
has resulted in the clarification of a series of important problems concerning the physics of Venus. Further development in the technology of radio astronomy and radar will make it possible to pose new problems. Among these problems which may be solved in the immediate years ahead with the aid of radio astronomical and radar measurements are, in our opinion, the determination of the physical parameters of that part of Venus not illuminated by the Sun, the mapping of the planet, and the investigation of the electrical properties of the surface and tne atmosphere.

In order to determine the parameters of the side of Venus not illuminatea by the Sun, it is necessary to continue radio astronomical measurements of the phase dependence of the planetary brightness temperature and to expland these to the entire band of wavelength from the millimeter to the decimeter waves, in which measurements of the non-illuminated side of the planet have been carried out. The measurements must encompass the full phase cycle of Venus, including the planet's superior conjunction.

The accomplishment of such measurements will be complicated by the fact that the antenna parameters of large radio telescopes are as a rule unstable in time and moreover depend on the position of the antenna, and therefore on the declination in space of the source of the radiation observed. The first circumstance leads to the necessity for conducting measurements through a method of comparing the intensity of radio frequency radiation of Venus with a standard source. In this connection, the angular dimensions of this source must be small in comparison with the antenna pattern width. Antenna parameter dependence on declination renderes impossible direct comparative measurements of Venus, the declination of which in the course of its phase cycle changes
by up to 45°, with one selected standard source, the declination of which /150
remains constant. Several standard sources with diverse declinations are required, with known relative intensities. The design of such a reference set of standard sources would also be of great value in radio astronomical measurements of other sources of radiation in space.

The comparison of standard sources with each other, and also with Venus, is more conveniently conducted through radio telescopes with a vertical-azimuth mount, for in this case the antenna parameters depend only on the altitude of the source and comparative measurements of two sources may be conducted when the altitudes of the latter are identical.

Measurements should also be conducted of the distribution of radio brightness of Venus on a series of wavelengths, including polarized radiation for the side of the planet illuminated by the Sun. It is extremely important to also continue radar measurements for the entire phase cycle of Venus.

The surface mapping of Venus is one of a number of problems which can hardly be solved in the foreseeable future without the application of radio physical methods of investigation. In fact, as has already been indicated above, observations of Venus in the optical band reveal no information concerning its surface. Direct probe investigations also do not solve the problem either, for the limited number of space vehicles which apparently may by directed toward Venus in the next several years will reveal only specific local information concerning the small areas in which they land.

Radio astronomical measurements of the distribution of radio brightness and of the polarization of the radio frequency radiation of Venus, and radar measurements of the distribution of the reflective features on the surface, conducted on several waves in the transparent band of the atmosphere of Venus, permit us to obtain a picture of the distribution of temperatures and electrical parameters of the planetary surface. The 10 cm wave in the band of transparence is suitable for conducting such measurements. The high resolution required for investigation of the distribution of radio brightness may be achieved through the installation of a radio telescope on a space vehicle performing a flight around Venus.

For the investigation of the electrical properties of the atmosphere of Venus, it is necessary to continue spectral measurements of the planetary brightness temperature in the ranges of decimeter and meter waves in order to clarify the ion ospheric properties of Venus. Spectral measurements are required in the range of sub-millimeter waves to obtain new data concerning /151
the nature of the absorbent layer in the planet atmosphere.

Radar measurements of the planet in the centimeter wavelength band may introduce an essential contribution to the investigation of the electrical properties of the atmosphere of Venus.

The continuation of investigations of variations in brightness temperature are also important.

However, both radio astronomical and radar investigations of Venus's atmosphere do not have uniform interpretations. Therefore, along with the continuation of measurements from the Earth, direct measurements of the atmosphere and of the surface of Venus with the aid of space vehicles are required. It is advisable to conduct on these vehicles the specific experiments of Venus that are impossible from the Earth. Among the measurements which may be carried out, for example, are measurements of the pressure and chemical composition of Venus's atmosphere, the determination of the rock material comprising its surface, and measurements of the planetary magnetic field.

A brilliant success of Soviet science and technology -- the first space contact with the planet Venus, established by the unmanned interplanetary station "Venus-3", permits us to hope that such experiments will be conducted in the near future. However, the development of programs of investigations with space vehicles does not decrease, but on the contrary increases, the necessity for the development of investigations of Venus from the Earth. Earth measurements provide initial data, on the basis of which decisions may be made concerning the choice of the most expeditious programs of space experiment. Earth measurements are required for the interpretation of space experimental data. Finally, Earth measurements are considerably more economical, and their dependability is considerably higher, than space experiments. Thus, according to an evaluation by American specialists [334], the cost of experiments conducted from the Earth is several hundred times less than the cost of space experiments.

Earth and space investigations must compliment each other: the former provides a basic mass of experimental material and the latter provides unique key data.

APPENDIX

TABLE 1. A LIST OF THE CONJUNCTIONS OF VENUS FROM 1956 TO 2000

Inferior Conjunctions			Superior Conjunctions		
Year	Date	Apparent Diameter	Year	Date	Apparent Diameter
1956	22 June	58″	1957	14 April	10″
1958	28 Jan.	63″	1958	11 Nov.	10″
1959	1 Sept.	59″	1960	22 June	10″
1961	11 April	59″	1962	27 Jan.	10″
1962	12 Nov.	63″	1963	30 Aug.	10″
1964	19 June	58″	1965	12 April	10″
1966	26 Jan.	63″	1966	9 Nov.	10″
1967	29 Aug.	59″	1968	20 June	10″
1969	8 April	59″	1970	24 Jan.	10″
1970	10 Nov.	63″	1971	27 Aug.	10″
1972	17 June	58″	1973	9 April	10″
1974	23 Jan.	63″	1974	6 Nov.	10″
1975	27 Aug.	59″	1976	18 June	10″
1977	6 April	59″	1978	22 Jan.	10″
1978	7 Nov.	63″	1979	25 Aug.	10″
1980	15 June	58″	1981	7 April	10″
1982	21 Jan.	63″	1982	4 Nov.	10″
1983	25 Aug.	58″	1984	15 June	10″
1985	3 April	60″	1986	19 Jan.	10″
1986	5 Nov.	62″	1987	23 Aug.	10″
1988	13 June	58″	1989	5 April	10″
1990	19 Jan.	63″	1990	1 Nov.	10″
1991	22 Aug.	58″	1992	13 June	10″
1993	1 April	60″	1994	17 Jan.	10″
1994	2 Nov.	62″	1995	20 Aug.	10″
1996	10 June	58″	1997	2 April	10″
1998	16 Jan.	63″	1998	30 Oct.	10″
1999	20 Aug.	58″	2000	11 June	10″

TABLE 2 Values $I_1(\tau, \varepsilon) \times 10^3$

ε \ τ	0	0,001	0,002	0,004	0,01	0,02	0,04	0,1	0,2	0,4	0,6	1,0	1,5	2	2,5	3,0	4,0	5,0	6,5
1,1	986	985	983	979	968	951	917	826	700	513	382	219	113	60	33	18	6	2	0
1,25	971	969	968	964	951	937	904	816	693	509	380	218	113	60	32	18	5	2	0
1,6	944	943	941	938	928	912	880	796	677	499	373	214	111	59	32	18	5	2	0
2,0	921	919	918	915	905	889	859	777	662	488	365	210	109	58	31	17	5	2	0
2,5	896	895	893	890	881	866	837	756	645	476	356	205	107	57	31	17	5	2	0
3,0	875	874	872	869	860	845	817	739	630	465	348	201	104	55	30	16	5	2	0
4,0	839	838	836	834	825	811	783	709	604	445	333	192	100	53	29	16	5	2	0
5,0	810	808	807	804	795	782	755	683	581	429	321	185	96	51	28	15	5	1	0
6,5	772	771	770	767	759	746	720	651	554	408	305	175	91	48	26	14	4	1	0
8,0	742	740	739	736	728	716	691	624	531	390	292	168	87	46	25	14	4	1	0
10	708	706	705	702	695	683	659	595	505	371	277	159	82	44	24	13	4	1	0
12,5	672	671	670	668	660	649	626	564	479	351	262	150	78	41	22	12	4	1	0
16	633	632	631	629	622	610	589	530	449	329	245	141	73	39	21	11	4	1	0
20	598	597	595	593	586	576	555	500	423	310	230	132	68	36	20	11	3	1	0
25	562	561	560	558	552	541	522	469	396	289	215	123	63	34	18	10	3	1	0
30	534	532	531	529	523	513	495	444	375	273	203	116	60	32	17	9	3	1	0
40	489	488	487	485	480	470	453	406	342	249	185	105	54	29	15	8	3	1	0
50	456	455	454	452	447	438	421	377	318	231	171	97	50	26	14	8	2	1	0
65	418	417	416	414	410	401	386	345	290	210	155	87	45	24	13	7	2	1	0
80	389	388	388	386	381	373	359	321	269	194	144	82	42	22	12	7	2	1	0
100	360	359	358	357	352	345	331	296	248	179	132	75	38	20	11	6	2	1	0

TABLE 3 Values $D_1(\tau) \times 10^3$ and $D_2(\tau) \times 10^3$

τ	0	0,001	0,002	0,004	0,01	0,02	0,04	0,1	0,2	0,4	0,6	1,0	1,5	2	2,5	3	4	5	6,5
$D_1(\tau)\times 10^3$	1000	998	996	992	980	961	924	833	704	514	383	219	113	61	33	17	7	2	0
$D_2(\tau)\times 10^3$	0	1	1	3	7	20	39	92	168	288	377	494	575	616	639	650	663	664	666

Tr. Note: Commas indicate decimal points.

TABLE 4

Values $I_2(\tau, b) \times 10^3$

b \ τ	0,001	0,002	0,004	0,01	0,02	0,04	0,1	0,2	0,4	0,6	1,0	1,5	2	2,5	3,0	4,0	5,0	6,5	10
0,90	105	105	104	103	101	98	88	75	56	42	25	13	7	4	2	1	0	0	0
0,78	248	247	247	244	240	232	211	182	137	105	64	35	20	12	7	2	1	0	0
0,61	493	493	491	487	479	465	427	373	290	229	147	87	53	33	21	8	4	1	0
0,37	993	992	989	982	970	947	884	793	647	536	376	250	171	119	84	44	24	10	2
0,20	1608	1606	1603	1594	1578	1549	1467	1347	1151	995	751	562	427	330	259	165	109	62	19
0,08	2524	2522	2518	2508	2490	2456	2360	2219	1931	1787	1486	1214	1014	862	742	566	456	321	166
0,03	3505	3503	3499	3487	3469	3433	3331	3180	2924	2712	2377	2066	1830	1643	1491	1256	1082	889	606
0,0067	5004	5002	4998	4986	4967	4930	4826	4670	4405	4184	3832	3499	3243	3036	2865	2593	2383	2139	1750
0,00055	7498	7496	7492	7480	7661	7424	7319	7162	6895	6672	6314	5976	5713	5501	5323	5040	4819	4558	4131
0,0`0045	10006	10005	10001	9990	9970	9932	9828	9670	9403	9180	8822	8483	8220	8007	7829	7545	7322	7060	6225

Tr. Note: On Table 4 and Table 5 commas indicate decimal points.

TABLE 5

Values $I_3(\tau, T_m, \beta\Delta h_0)$

T_m, °K	$\beta\Delta h_0$, °K \ τ	0,001	0,002	0,01.	0,02	0,04	0,1	0,2	0,4	0,6	1	2	2,5	3	4	5	6,5
300	—10	0,6	1,2	5,8	11	22	50	89	145	185	233	280	288	292	296	296	296
	—40	0,60	1,2	5,8		22	50	88	144,5	183	230,6	275		285	287	288	—
	—160	0,59	1,2	5,8	11,4	22	50	87	141	177	220	254	257	257,6	—	—	—
400	—10	^,80	1,6	7,8	15,2	29	67	118	194	246	311	374	385	390	395	396	397
	—40	0,8	1,6	7,8	15,2	29	67	118	193	245	308	369	379	384	386	387	387
	—160	0,8	1,6	7,8	15,2	29	66	117	190	239	298	348	354	356	—	—	—
600	+150	1,2	2,4	11,6	22,8	44	101	179	295	377	482	590	611	623	637	643	648
	+500	1,2	2,4	11,7	22,9	44	102	183	305	394	513	651	683	705	731	747	762
1000	500	2,0	4,0	19,4	38	74	169	301	499	641	325	1027	1070	1098	1129	1146	1162
2 000	500	4,0	7,9	38,8	76	147	336	597	985	1258	1606	1966	2038	2080	2124	2145	2161

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